



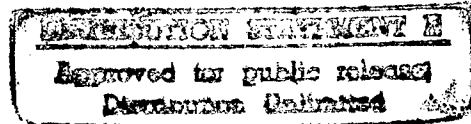
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Oceanography and the Navy

Future Directions

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Oceanography and the Navy

Future Directions

Navy Review Panel
Ocean Studies Board
Commission on Physical Sciences,
Mathematics, and Resources
National Research Council

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Preface

At the request of the Chief of Naval Research, the Navy Review Panel of the Ocean Studies Board recommends oceanographic research topics for future accelerated research initiatives. As is the case with their core research program, the Office of Naval Research funds accelerated research initiatives in promising scientific areas that are important in the long term to naval operations. To understand better the research needs of the Navy, the panel discussed basic (6.1) and applied (6.2 and 6.3) research with program managers from the Office of Naval Research, the Naval Research Laboratory, the Naval Oceanographic Research and Development Activity, and the Office of the Oceanographer of the Navy. To broaden our perspective of recent progress and future prospects in the oceanographic subdisciplines, we enlisted many colleagues, whose somewhat different writing styles are still in evidence in the final report. Our summaries of naval relevance and of scientific trends are included to provide background for our recommendations and are not intended to be comprehensive or definitive reviews of either the basic science or naval research.

Michael Gregg
Chairman

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Executive Summary

New technologies and global observing networks have transformed our understanding of the ocean from what we knew 20 years ago and promise a similar overturn during the next two decades. Because scientific predictions in specific areas of greatest concern to the Navy are notoriously erratic, the Office of Naval Research supports those topics that combine promising scientific advances with long-term naval relevance.

Anti-submarine warfare (ASW) is the most important naval problem, a situation that will continue for the foreseeable future. The ASW emphasis, however, has changed. During the last 15 years, small-scale hydrodynamics were emphasized, to aid the tactical localization of submarines detected by long-range surveillance. Because of the dramatic quieting of Soviet submarines, surveillance is less effective and the research emphasis has changed to low-frequency long-range acoustics. This requires better understanding of variability across ocean basins, and especially of the 200-km-scale vortices that are the ocean's analog of synoptic weather systems. In addition, sound traveling long distances often scatters repeatedly from both the sea surface and the sea floor. These interactions must be better understood to improve acoustic surveillance systems. The naval emphasis on long scales coincides with the scientific emphasis on climate and global change, offering a set of problems combining important scientific progress and long-term naval relevance. Nevertheless, not all of the topics recommended herein by the panel are large-scale; some small- and intermediate-scale processes cause large-scale effects and must be considered.

Since the early 1980s, the Office of Naval Research (ONR) has put about half of its funds into accelerated research initiatives (ARIs). Lasting 5 years, ARIs are focused efforts on specific problems. The panel's recommendations for future ARIs are summarized below, grouped by the program areas used by ONR.

- Physical Oceanography

- *Interactions and modeling of mesoscale and submesoscale processes.* Although mesoscale and submesoscale interactions do the principal horizontal mixing of water masses, numerical modeling of these scales is much less advanced than that of the basin-scale general circulation. Because of the increased importance of the mesoscale to acoustic submarine

detection, shipboard models are being used by the Navy, making their improvement more urgent.

- *Horizontal and vertical mixing in the mid-ocean and near its edges.* The relative importance of vertical versus horizontal fluxes in establishing and maintaining both western boundary currents and the main thermocline remains uncertain, leading to radically divergent theories. Simultaneous measurements of internal waves, turbulence, chemical tracers, and horizontal advection are needed to constrain parameterizations in numerical models of small-scale processes.

- *Near-surface physics and air-sea fluxes.* Except for the microlayer in the top centimeter of the ocean, little is known about the upper 5 m because most measurement techniques do not work in this difficult regime. This is a serious problem that limits our ability to parameterize air-sea fluxes and to predict optical and acoustic transmission through the sea surface. New instruments and techniques are needed.

- *Deep convection.* Sustained cooling at high latitudes forms the intermediate and deep water that fills the world ocean. In spite of its importance, too little is known about how this occurs to define the force balance or even the spatial scales. Coordinated measurements and modeling are needed to obtain a first-order description of a process of global significance that occurs in a major submarine operating area.

- Coastal Sciences

- *Nearshore processes.* Steady near-bottom offshore currents (undertow) and turbulence in the surf zone play key roles in sand transport and beach erosion but too little is known about the details to develop realistic models. Laboratory experiments and instruments capable of operating in the surf zone are needed. Understanding the physics of the surf zone will aid amphibious operations, help find buried mines, and improve the design of structures situated in the surf zone.

- *Intermediate-scale shelf dynamics.* ASW and mine warfare are made particularly difficult near coasts by the closeness of the bottom and by complicated hydrodynamics and water masses. For the same reasons, our understanding of ocean dynamics over continental shelves lags that in the deep ocean. Recently we have realized that thermal and current variability on the shelves is dominated by alongshore scales of 1 to 50 km. A focused effort is needed to understand these scales and incorporate them into numerical models.

- *Small-scale turbulence.* Although Jefferies showed in 1920 that most tidal dissipation occurs in shallow seas, turbulence measurements have been focused in the deep ocean. Measurements of turbulence in coastal waters are needed for a first-order description of the mechanisms and rates of what is likely to be a dominant process.

- Marine Geology and Geophysics

- *Continental margins.* Although the geophysical structure of continental shelves and margins is important to marine geophysics, it is being overlooked in NSF programs, which concentrate on the floor of the deep sea. Because the subject is also vital to coastal ASW and mine warfare, a focused ONR program is needed.

- *Low-frequency acoustics.* Because of the quieting of high-frequency noise on Soviet submarines, future ASW acoustics will emphasize transient low-frequency signals. Transmission of these signals necessarily involves interactions with the bottom. An extensive field program supported by theoretical modeling of wave propagation is needed.

- *Sediment dynamics.* Future ASW sonar systems will increasingly be large bottom-mounted arrays on continental shelves, the zones where very low frequency (VLF) acoustic energy interacts most strongly with the bottom. Thus, coupling of process oriented efforts and field studies to determine sediment dynamics in a variety of environments is essential.

- *Quantitative mapping and geomorphology.* The structure and composition of oceanic crust are established when the crust is formed at spreading ridge crests. Once the processes of crustal formation at ridge crests are understood, marine geophysicists believe they will be able to use high-resolution bathymetry to infer structure and composition below the sea floor. This predicative capability will allow the Navy to determine the subsurface structures and acoustic/sediment properties needed for using low-frequency acoustics without having to do detailed studies below the sea floor.

The NSF is sponsoring a large study of active ridge crests to determine how the crust is formed. To utilize the expected results of the ridge crest study, the panel recommends that ONR determine how to use the new tools for high-resolution bathymetry (SEABEAM, SEAMARC, and GEOSAT) to infer subbottom structure and composition. Work is needed now to examine how well the subbottom properties can be inferred and how tightly the bathymetry surveys must be run.

- *Structure and formation of the Arctic Basin.* Information about the tectonic history of the Arctic Basin is sketchy. In fact, there is no certainty that the Arctic Basin was formed by the same processes that produced continental shelves and ocean basins at lower latitudes. For instance, much of the sediment entering the Arctic was derived from glaciers and deposited on shelves scoured by ice. Consequently, the sedimentary history probably differs from that of the other ocean basins. Multichannel seismic surveys and studies of sediment dynamics can answer some of these questions and provide the Navy with data needed to predict acoustic scattering from the bottom.

• Oceanic Biology

- *Bio-optics.* Except for small colonies clinging to hydrothermal vents, all life in the sea ultimately obtains its energy from light. Consequently, understanding how light is transmitted, absorbed, and scattered is central to the biology of the upper ocean, as well as to optical detection of submarines. Theoretical advances and new optical technology provide novel ways to explore how phytoplankton and light interact and how they affect upper ocean dynamics. Because these interactions vary with location, the few localized studies done so far need to be generalized to broader regions, especially to the sediment-rich nearshore waters.

- *Plankton distributions and their relation to fluid dynamics.* By virtue of their position at the base of the food chain, plankton affect the distributions of higher marine organisms, thereby also determining the distribution of biologically produced acoustic noise in sonar systems and the scattering of high-frequency sound used to find targets. Therefore, one of the most fundamental problems of biological oceanography is the definition of plankton distributions and the determination of how the distributions result from interactions with the fluid motions. An interdisciplinary program is needed to measure plankton distributions over the same space and time scales as physical variables and to relate the distributions to the flow field. The latter requires the application of fluid dynamics and modeling.

- *Biological oceanographic modeling.* Although new sensors, such as color scanners in satellites, have greatly improved the measurement of biological populations, the improved

measurements have not led to better theories or numerical models. Biological oceanographers are often skeptical of modeling as a result of many failures in previous attempts. It is the panel's opinion, however, that progressive biological modeling is possible as a result of a much better understanding of physical oceanography and of the new sampling tools for biological distributions. This combination promises a sound basis for treating the physical environment and a means of testing the predictions. Even a modest start toward good models will produce a large jump in understanding the biology. This, in turn, will provide the Navy with useful predictions of bioluminescence and other ASW indicators.

- Arctic Sciences

- *Arctic drifting buoys.* Basic oceanographic data for the Arctic (water temperature, velocity, and salinity profiles, and internal wave and front locations) are poorly known and difficult to collect, especially in the Central Arctic and the Soviet sector. Deployment of long-lived floats and ice buoys would lead to a greatly improved picture of overall arctic circulation, including levels of mesoscale activity, internal waves, and local variability. This descriptive data will also provide needed detail about the spatial variability affecting long-range acoustic propagation.

- *Ice dynamics: thickness and deformation.* Until recently, models of ice dynamics could not be tested due to lack of adequate measurement technology. Submarine and bottom mounted sonars, along with SAR satellite imagery, will allow great progress in modeling properties of ice, as well as arctic geographical variability in its thickness. Predicting ice thickness is necessary for extensive submarine operations and for understanding the lid that makes the Arctic Ocean unique.

- *Deep-water formation.* Much of the world's climate- controlling deep water forms in the Greenland Sea; U.S. participation in the 5-year Greenland Sea Project will substantially increase our understanding of the convection feeding this process. The deep water sinks much deeper than submarine operating depths and causes most of the variability affecting acoustic propagation.

- *Shelf-basin water exchange.* Arctic hydrography is significantly controlled by the movement of cold, saline shelf water into the deep basin. A research program to study this exchange, especially in the vital Chukchi and Barents seas, should be initiated. Since these are major operating areas for Soviet submarines, any gains in our sparse data base are important.

- Oceanic Chemistry

- *Marine chemical modeling.* Numerical modeling is essential to understanding the interactions between chemical, biological, and physical processes in the upper ocean. Chemical processes occur on a wide range of temporal and spatial scales; new data analysis techniques must be developed to maximize utility of the Global Ocean Flux Study and World Ocean Circulation Experiment (WOCE) data sets. Benefits to the Navy will be indirect, resulting from the tight constraints tracers place on physical and biological models.

- *Measurement advances.* Lack of appropriate measurement techniques limits effective chemical oceanography. Development of new analytical technology is essential for naval purposes, for example, measurement of trace substances that may be useful in detection of other vessels.

Physical Oceanography

Physical oceanography, the study of the fluid mechanics of the sea, seeks a fundamental understanding of the transfers of mass, momentum, energy, heat, and salt in the ocean and of the fluxes between the ocean and the atmosphere. In addition to being of intrinsic interest as a major aspect of the earth's dynamics, understanding the physics of the sea is vital for climate dynamics, waste management of pollutants, marine ecology, and many aspects of naval operations. Reliable instruments and powerful computers developed since the 1960s have transformed the field from a largely descriptive endeavor, reminiscent of natural philosophy, to a modern quantitative science. Major discoveries of unexpected phenomena in physical oceanography continue, but direct comparisons between observation and theory are now routine.

Although the dominant physical processes in the ocean vary greatly with length and time scales, depth, and geographical location, they fall into a few broad categories.

- *The general circulation* considers length scales up to the size of ocean basins and periods of months to years. At shallow depths, the general circulation is driven by time-varying winds and constrained by the geography of the continents and the earth's rotation. At greater depths the mean slope of the sea surface and variations in the sea surface buoyancy flux produce the mean flow. Both the near-surface and interior motions redistribute heat and salt supplied at the surface by air-sea interactions. For example, the most dense water is produced under ice floes in the Antarctic and then sinks and spreads along the bottom throughout the world ocean.

- *The mesoscale* has length scales of a few to hundreds of kilometers and periods of weeks to months. Analogous to the cyclones and anticyclones that form the weather patterns in the mid-latitude atmosphere, the mesoscale contains most of the ocean's eddy kinetic energy. The large eddies that dominate the mesoscale are most intense near major current systems, such as the western boundaries of ocean basins and the Antarctic Circumpolar Current.

- *The small scale* extends from a few kilometers to millimeters and includes periods of a day to seconds. Small-scale processes complete the mixing of variations introduced over global scales. The most energetic are internal waves with periods from the local pendulum day (24 hours at 30° latitude) to the stability period of the stratification (typically 20

minutes). Most of their kinetic energy has vertical scales of tens to a few hundred meters and horizontal scales up to 100 times greater. Generated by a multiplicity of mechanisms, internal waves propagate energy vertically in the water column. Their turbulent breakdown over scales of meters is one of the mechanisms producing molecular mixing, which occurs over scales of 10 cm (for momentum) to 1 mm (for salt).

Recent progress in understanding the dynamics of the ocean on these scales is outlined below, partly focused on particularly important oceanic provinces and geographical locations, such as the upper ocean and the equator. Other subdiscipline reports on coastal sciences (chapter 2) and arctic sciences (chapter 5) also cover important aspects of physical oceanography.

TRENDS AND PROGRESS

Understanding the ocean for any purpose ultimately demands comprehending it as a complete, coupled fluid system spanning two-thirds of the area of the earth's surface. The ocean is turbulent, and a characteristic of turbulent fluids is that no regions or scales can be studied in complete isolation from the rest of the system.

Until recently, however, observations of the ocean were limited to regions of a few hundred kilometers square, and even then only for short periods of time (limited by ship and instrument endurance). Over the past decade or so, the oceanographic community has come to realize that for many problems (climate, ocean forecasting for the military, biological understanding, ocean dumping, environmental impact) further progress demands the observation of the global ocean on multiyear time scales. Not coincidentally, parallel technical progress in a number of different areas related to oceanography makes it possible, for the first time, to contemplate treating the global ocean as a closed system.

General Circulation and Remote Sensing

The largest scale of oceanic motion—the general circulation—is the most persistent; any mechanistic predictive model of the ocean has to get the largest scales right or it risks biasing or invalidating all the smaller scales of motion. One great lack in large-scale modeling is an adequate data base—even those pieces of physics that we believe are well understood have not been sufficiently tested against reality. For example, the fundamental physics of the wind-driven circulation of the oceans has been explored in analytical and numerical models for four decades, but the only winds available to drive the models are from a century of ship observations (mostly visual estimates, mostly at middle to low latitudes, mostly in the Northern Hemisphere, and mostly biased toward low winds) and from 3 months of the SEASAT in 1978. Even if the models could be adequately driven, however, comparing the calculations in detail with observed data would be extremely difficult.

One reaction to the global nature of the general circulation and to the demand for an improved global data base on the forcing functions and the oceanic response is the massive, international global observational program entitled the World Ocean Circulation Experiment (WOCE). As envisaged now (1988), beginning around 1991 many of the world's oceanographers—in the United States and most other maritime countries—will embark on a nominal 5-year effort to observe the ocean well enough to test global circulation models that can simulate the ocean climate. These models will undoubtedly be used for biological and chemical calculations and may provide regional and global forecasts.

The past 15 years has been a period of technical development that will contribute

directly to the implementation of WOCE; the scheduling of WOCE is, in fact, motivated by these developments. They include the following:

- satellite sensors specifically designed to measure the oceanic wind field (scatterometers) and sea-surface elevation changes (altimeters);
- long-lived, highly accurate, self-contained in situ measurement systems (e.g., for velocity and temperature);
- fast, extremely precise chemical tracer measurement techniques (e.g., for tritium and fluorocarbons); and
- computer power and computer models capable of handling massive data sets.

Two satellite altimetric missions (the U.S.-French Topex/Poseidon mission and the European Space Agency's ERS-1) are centerpieces, largely setting the timetable and providing global observations. Planning for WOCE received a serious setback in 1986 with the abrupt cancellation by the Secretary of the Navy of the so-called NROSS satellite. This spacecraft was to have carried a wind-measuring scatterometer provided by the National Aeronautics and Space Administration (NASA). Efforts are being made to explore alternative space platforms and coverage (including the conventional over-ocean meteorological analyses provided through the European Centre for Medium-Range Weather Forecasting) and to provide a careful analysis of existing ship data of winds over the ocean. The oceanographic community also believes that the WOCE program will be able to leave in place (or install) a cost-effective, in situ global observational system that will continue to provide information on the ocean as a turbulent fluid, with all its implications for basic science, climate, weather, biology, and naval operations.

The overall pattern of the general circulation is clear. The wind-driven forcing and the meridional blocking of the continents tend to maintain large counterclockwise gyres poleward of the westerly winds in the "roaring forties" latitudes, and clockwise gyres at mid-latitudes between the trade winds (easterlies) and the westerlies (Figure 1-1). There is a strong westward intensification of the gyres that is demanded by an oceanic version of conservation of angular momentum; the Gulf Stream is an example of this westward intensification.

The more complicated physical and mathematical problem occurs on the northeastern side of the gyres in the Atlantic Ocean where thermodynamic forcing from the atmosphere tends to ventilate the surface waters which, as their density increases, slowly sink and slip southward and then finally westward as they go deeper and deeper beneath the unmodified surface waters above them. This process of *subduction* is a current research focus that conceptually closes the overall loop of the general circulation (Figure 1-2): winds dominate the large horizontal gyres, while thermodynamically-driven subduction contributes to the vertical component of the circulation.

This oversimplified background to circulation physics serves to illustrate how even the largest, slowest scales of oceanic motion involve a large number of complex processes that can only be studied individually in the early stages of their understanding. Subduction is still at an early stage and it is ready to be studied as a distinct physical process that must be better understood before an array of air-sea interaction models is complete, and before a complete thermodynamic ocean circulation model can be prepared. Recent interplay between numerical and theoretical subduction studies has suggested that homogenization from diffusion may make it harder to observe subduction than was originally thought; this guidance will make the evolving field programs more sensible and cost effective.

Another crucial piece of general circulation physics is the process known in oceanography as deep and intermediate "water formation." More precisely, it means the modification of

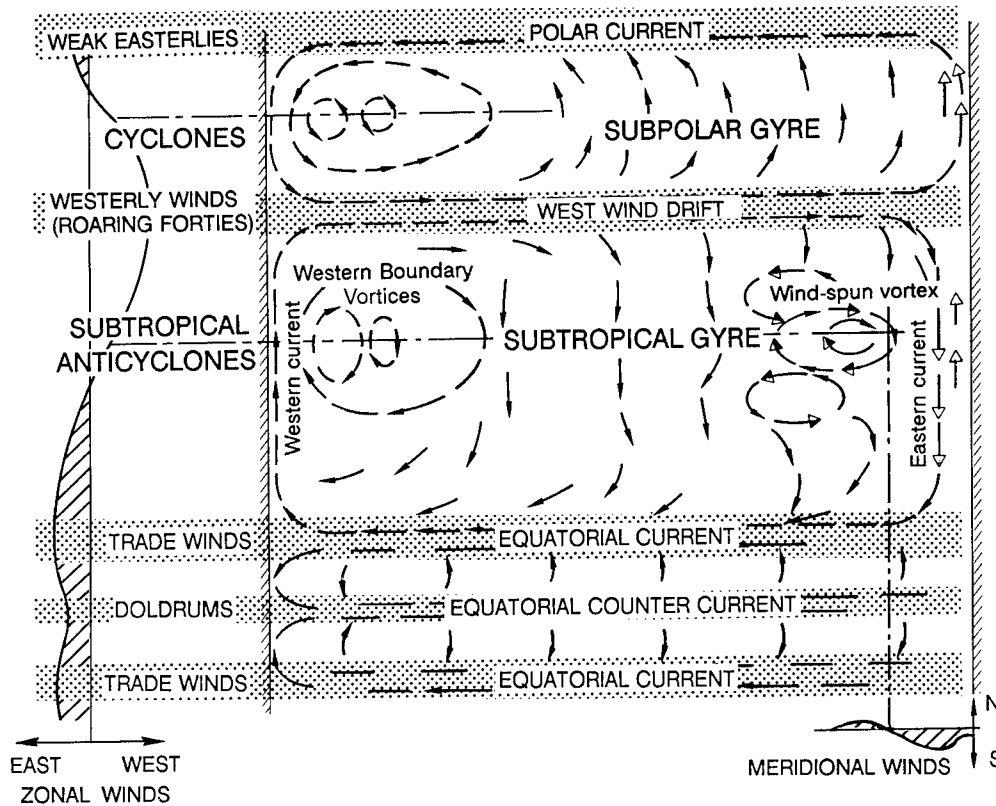


FIGURE 1-1 Schematic presentation of circulation in a rectangular ocean resulting from zonal winds (filled arrowheads), meridional winds (open arrowheads), or both (half-filled arrowheads). The width of the arrows is an indication of the strength of the currents. The nomenclature applies to either hemisphere, but in the Southern Hemisphere the subpolar gyre is replaced largely by the Antarctic Circumpolar Current (west wind drift) flowing around the world (Munk, 1950).

the density of a water mass by thermomechanical action; an example is surface cooling from cold, dry winds until the surface water gets denser than the water underneath it. Vertical convection then takes place, with associated mixing and homogenization of the volume of involved water. If the "new" (meaning modified) water mass is dense enough to sink to the bottom, then "bottom water" is formed and may spread—detectably—over entire ocean basins.

Much of the bottom and deep water in the oceans is formed in this way by air-sea interaction at high latitudes. The sites of major deep water formation are in the Greenland, Norwegian, and Labrador seas in the Northern Hemisphere, and the Weddell Sea and gyre in the Southern Hemisphere. Although this unique oceanographic process seems rather arcane, it is an important link in the modeling of the large-scale circulation; it is responsible for much of the contrast in water properties that allows hydrographic data to yield circulation inferences; and it may have important biological and chemical consequences as well (e.g., removal of CO_2 from atmospheric contact).

Deep water is formed over remarkably small space (a few kilometers) and time (hours to days) scales, but affects the large-scale circulation, further illustrating how modern oceanography cannot easily be categorized into distinct process scales.

A theme throughout general circulation discussions is the need for global observations,

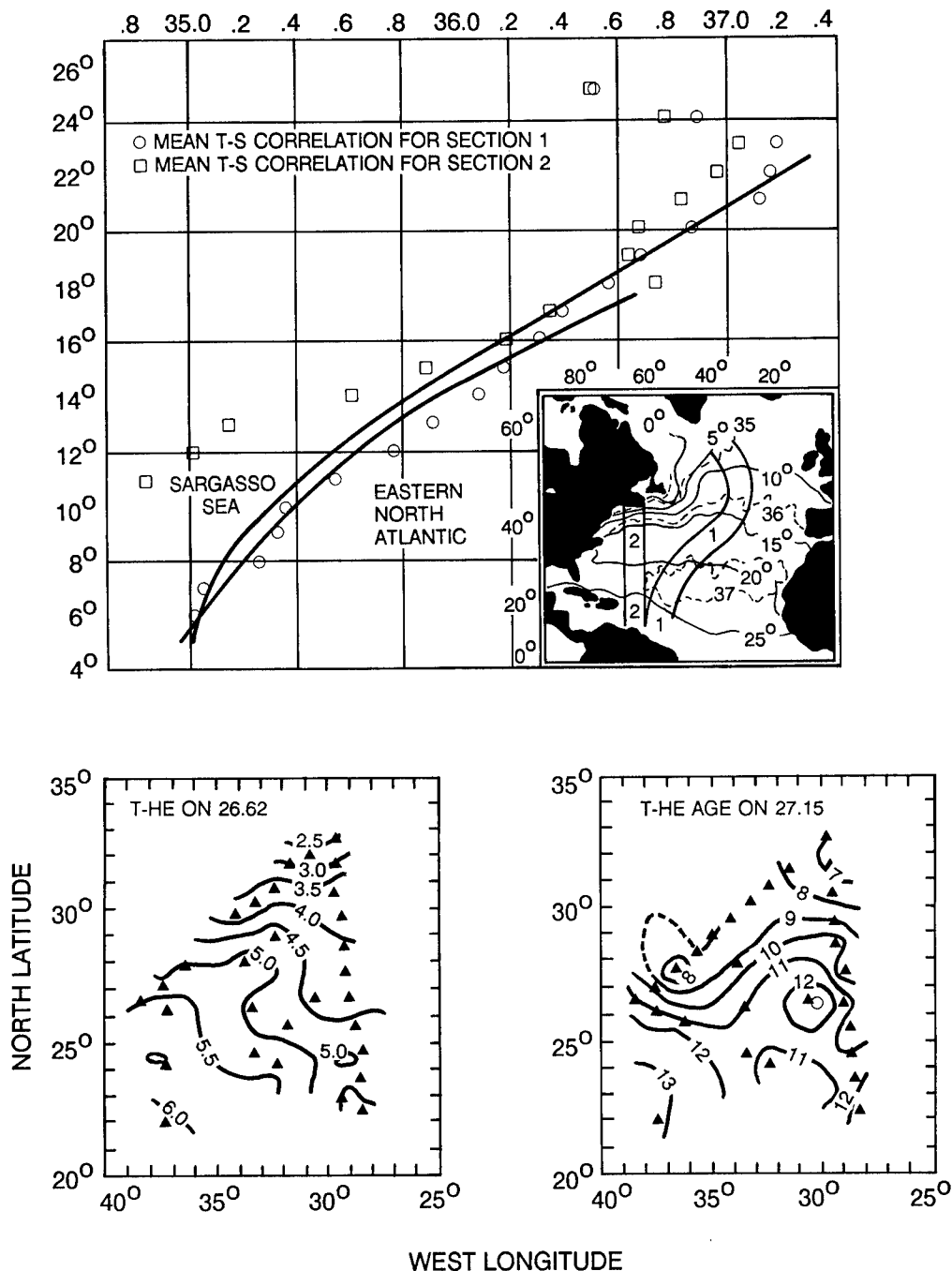


FIGURE 1-2 The effects of subduction of surface waters. The upper panel (Iselin, 1939) shows the strong similarity between the temperature-salinity (T/S) properties of surface water (symbols) and in a vertical profile in the region (lines), which implies that the waters of the main thermocline acquire their T/S while at the sea surface, and then conserve T/S after they are subducted and flow through the main thermocline. The lower set of figures shows the estimated time since thermocline water was in contact with the sea surface (or age) inferred from radiochemistry measurements (Jenkins, 1987). The left panel is at a depth of about 270 m, and the right panel is at a depth of about 625 m. These data also imply a subduction of surface waters in that age increases with increasing depth, from northeast to southwest, and in the direction of the mean flow. These modern data also show the rate of subduction, which the older T/S data alone cannot.

hence the importance of remote sensing, especially from satellites. The superficial data from satellites provide only part of what is needed. A rapidly growing and potentially powerful tool is the wise use of computer models to assimilate sparse but accurate in situ data and global, but crude, remotely-sensed data. This field must be nurtured to maturity.

Mesoscale Processes

In the 1950s, systematic eddy studies began in the western North Atlantic and progressed to the large international field programs MODE and POLYMODE of the 1970s. Subsequent efforts have used remote sensing and moorings to obtain limited global descriptions of mesoscale variability, and to understand mesoscale eddy dynamics and its role in the general circulation.

One large effort in the 1980s has been in the North Pacific, where over 30 long-term moorings have been maintained at mid-latitudes by U.S. and Japanese scientists. Both narrow western boundary currents and broad mid-latitude flows were found to be sources of mesoscale turbulence. The Kuroshio Current off Japan is a major source of eddy activity in the western Pacific. The westward-flowing subtropical circulation south of 30°N appears to be a second source, based on observed energy transfers to 30-km-scale eddies from the 1000-km-scale general circulation northeast of Hawaii. Energetic eddies have also been found in the California Current, the Arctic Ocean, the South Atlantic, the western Indian Ocean, the Antarctic, and all three equatorial oceans. Interaction with the coastline appears to be one generating factor in the Arctic, and horizontal shear of strong zonal currents is a factor at the equator.

Satellite altimetric remote sensing of the mesoscale is being developed. Satellite orbits are known well enough that radar can define the sea surface elevation within tens of centimeters over the horizontal scale of mesoscale eddies. Data from the altimeter on the SEASAT satellite in 1978 confirmed the global importance of mesoscale activity near the western boundaries of ocean basins (Figure 1-3) and provided new descriptions of mesoscale variability around the Antarctic. The GEOSAT altimeter is confirming and describing tropical ocean mesoscale motions on a basin-wide scale. These latter observations are of special interest owing to the effect of the tropical ocean on global weather patterns. Eddies appearing near the equator annually between August and January produce large meridional transports of heat and momentum. A complementary technique, acoustic tomography, is similar to the Computerized Axial Tomography (CAT) scans of medical tomography. Fluctuations in acoustic travel times across arrays of transmitters and receivers can be inverted to estimate the temperature changes accompanying mesoscale eddies.

Significant advances in modeling are being made possible by large increases in the computing power available to the oceanographic community. A major accomplishment is development of full-basin, eddy-resolving general circulation models for the North and South Atlantic and for all the equatorial oceans (Figure 1-4). The overall result is that eddy viscosity models (coarse grids, parameterized smaller-scale motions) do not replicate eddy-resolving model results, principally because the eddy field has an apparent vertical and a horizontal variation of mixing, which the eddy viscosity models cannot replicate. Eddies also drive or rectify significant deep circulation patterns which the eddy viscosity models do not. The Gulf Stream, in particular, has been shown to contain a number of deep gyres whose driving potential is derived from eddy convergence.

A second area of modeling progress is the prediction of mesoscale evolution, particularly of the tropical mesoscale, which is composed of both wind-driven motions and turbulence. An operational version of the Pacific Ocean model developed at the Geophysical Fluid

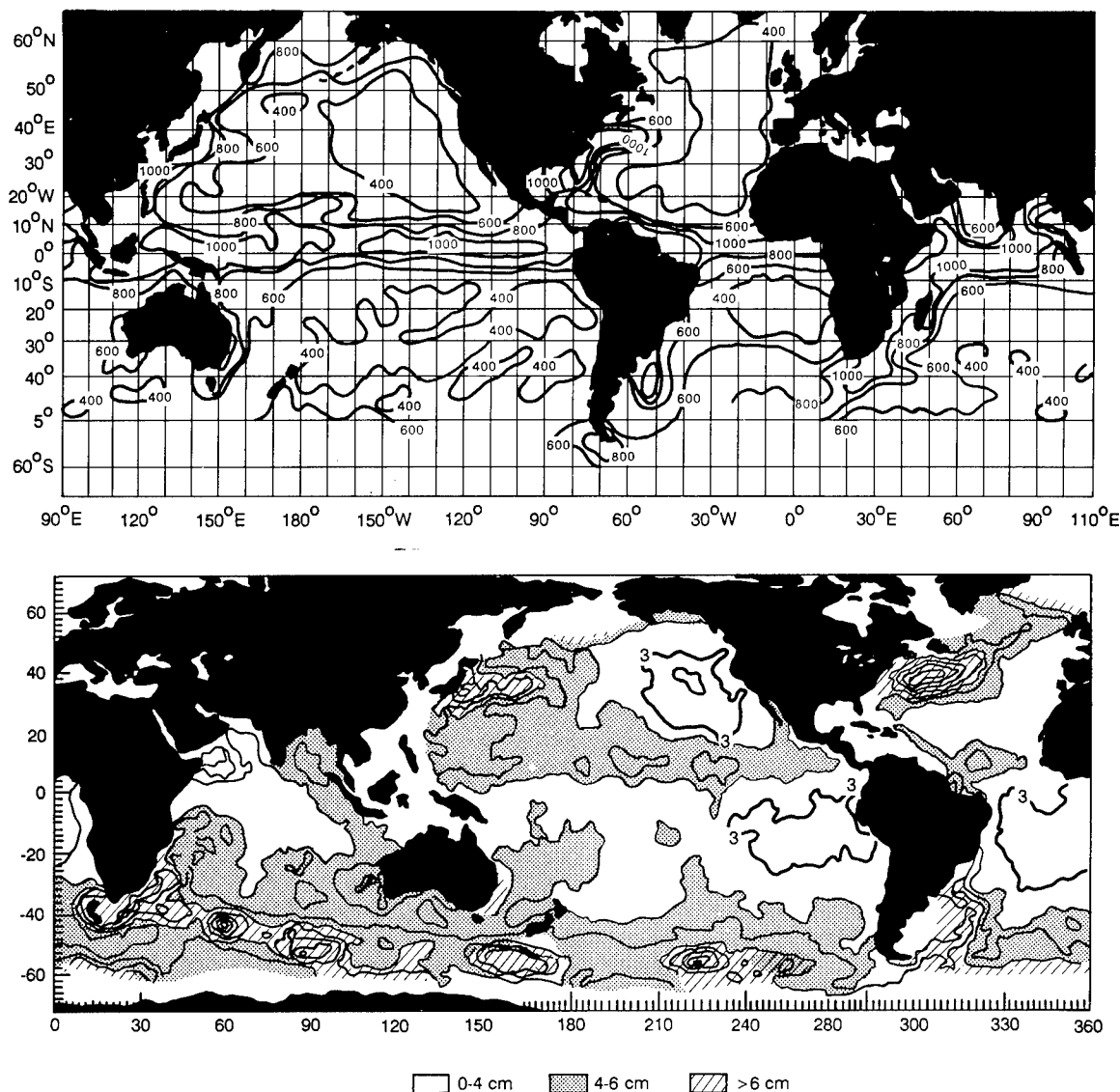


FIGURE 1-3 Top: eddy kinetic energy per unit mass based on 5° square averages of ship-drift data (Wyrski, 1976). Bottom: mesoscale sea height variability from the SEASAT altimeter, September-October 1978, averaged over 2° squares (Cheney, et al., 1983).

Dynamics Laboratory (GFDL) has been installed at the National Meteorological Center (NMC). It runs on a daily update, with air-sea interaction input from fluxes from the atmospheric circulation model. This model and similar endeavors at several universities are teaching us how to predict wind-driven El Niño phenomena and the seasonal evolution of mesoscale turbulence in tropical oceans. Considerable progress has been made in modeling the upper ocean variability in the Indian Ocean over seasonal and interannual scales by several laboratories in the United States and France.

Model predictions of discrete eddies in limited areas of mid-latitudes have also been developed. The limited area models can be integrated from initial conditions for a few eddy rotations and have been run for portions of the Gulf of Mexico, the Gulf Stream, the South

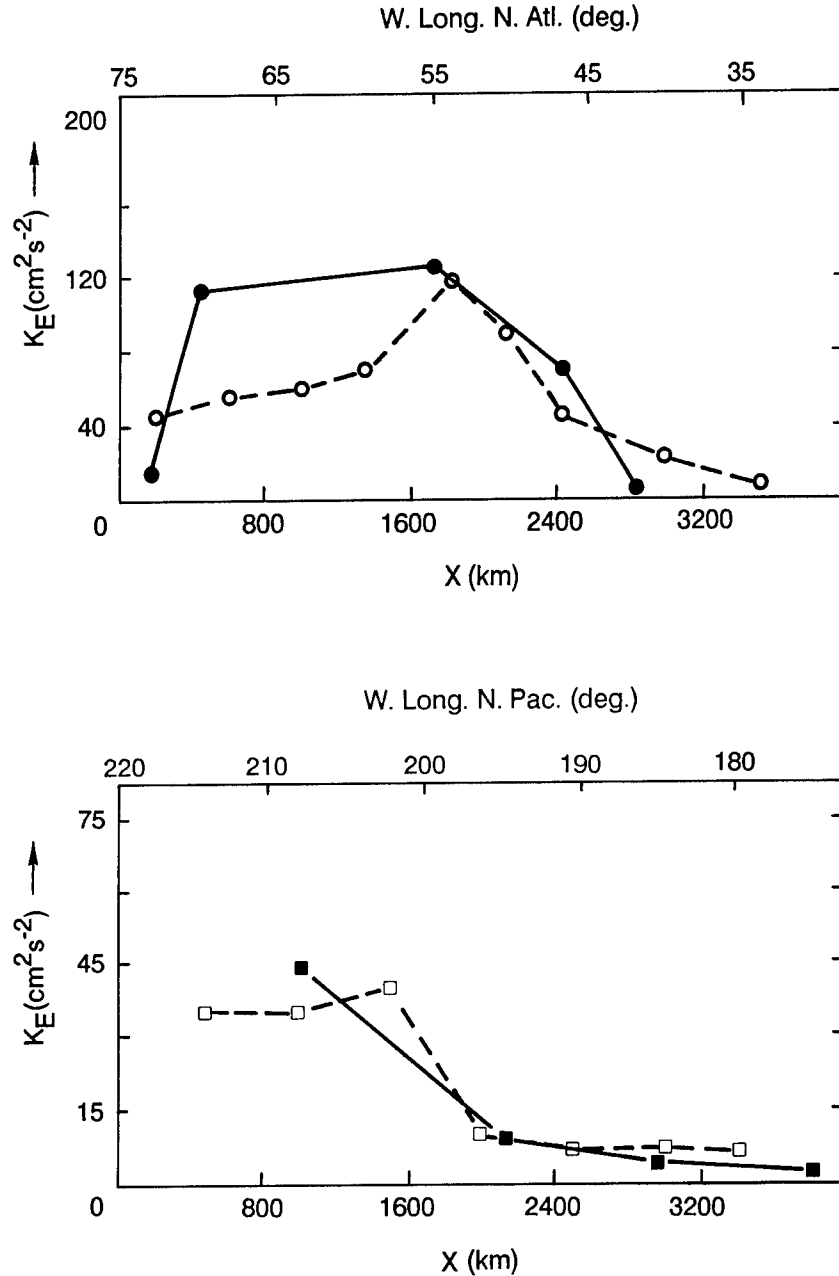


FIGURE 1-4 Comparison between numerical model (open symbols, dashed lines) and direct observations with moored current meters (solid symbols, solid lines) for eddy kinetic energy at 4000 m depth in the western North Atlantic (top) and western North Pacific (bottom). (Schmitz and Holland, 1986)

Atlantic, and the California Current. These predictions are of considerable value for naval acoustic surveillance systems.

Successes in both remote sensing and modeling have motivated current efforts to combine these two approaches to produce real-time and predictive pictures of ocean thermal features. They are needed for climate studies and naval acoustics, as well as for biological and chemical transport studies. Optimism for success is based on the demonstrated ability

of satellites to measure the surface winds, the surface elevation of the eddies, and momentum fluxes that drive the ocean circulation, all of which are used to develop and verify numerical predictions.

Another trend is observation of interactions between meso-scale eddies and the mean circulation. Now that eddies are known to exist, scientific questions about their sources of energy and about the eddy-forced mean flows are of interest and importance. Large current-meter and float arrays deployed over long periods are required; these large-scale projects are expensive. Mid-depth floats that are located by satellite (pop-up floats) or that transmit their received acoustic location to satellites (RAFOS floats) are important new tools.

Small-Scale Processes

Publication of model internal wave spectra in the early 1970s propelled a decade-long spurt of rapid progress. Derived from observations, the analytically simple energy distribution among space and time scales provided a framework for relating measurements as disparate as isotherm vertical displacement and horizontal velocity, even when measured at different times and places. Specification of the spectra permitted calculations of energy transfer rates from wave-wave interactions, providing the first serious estimates of internal wave dynamics.

By the early 1980s the impetus for theoretical work on internal waves was largely spent, but internal wave observations are now imbedded in most programs studying large-scale processes or geographical regions. Among the principal findings, all of which are at variance with the available model spectrum, are the following:

- Energy levels beneath parts of the arctic ice pack average only 2 percent of those in the open ocean. Turbulent dissipation rates are also very low, and internal wave generation is weak, presumably due to ice shielding the water from the wind stress.
- Internal wave energy levels in the main thermocline show an unexpected seasonal cycle that lags the surface wind stress by several months, suggesting very long relaxation times in the internal wave field.
- Two-dimensional horizontal vortices with the same space and time scales as internal waves are now known to be possible in the ocean. Virtually nothing is known about the energy contained in these motions or about their dynamics. Both observational and theoretical efforts are being made to explore these vortical modes.
- Acoustic profiling of velocity in the upper kilometer reveals an internal wave spectrum strikingly different from the current model, which is essentially the same as the one introduced in the early 1970s. Integrals nevertheless yield the same net isotherm displacements and horizontal velocities as the model.

The theoretical implications of this spectrum have not been explored, but the dynamics may be very different from those of the present model. Two-dimensional horizontal vortices may be an important factor. These new observations demonstrate that our understanding of internal waves is incomplete and that our understanding 10 years hence will surely differ from that of the present.

Essentially all of the theoretical ideas on internal waves and mixing have been driven by modern observational evidence. Mixing coefficients were, and largely still are, the adjustable parameters of analytical and numerical models, chosen to fit calculated large-scale variables to observations without regard to direct knowledge about mixing. Increasingly, however, measurements of velocity and temperature dissipation rates, in various oceanic regimes, are



FIGURE 1-5A Evolution of an internal wave as it breaks and mixes the surrounding water, as photographed by divers who had dyed the wavy surface (Woods, 1968).

illuminating patterns of mixing and providing bounds for the coefficients used in models. These observations have progressed from relatively infrequent exploratory probes in the late 1960s and the 1970s to intense sampling of regions being simultaneously studied at larger scales during the 1980s. This integration in scales is a recognition that oceanic process does not exist in isolation, and that each time and space scale is embedded in still larger time and space scales.

Turbulent fluxes remain elusive, however, as fluxes have yet to be measured; out of necessity they are estimated from dissipation rates, using relationships derived by the assumption that turbulent dissipation and production balance locally. Laboratory experiments are now being conducted to investigate these estimation techniques, but the prevailing sentiment is that the estimates of the mixing levels found in typical thermoclines are too high. A fundamental need is to determine how and where the mixing takes place; the tools are now available.

Although internal wave breakdown has long been suspected as the principal agent producing mixing, little is known of the mechanisms. Figure 1-5A illustrates two of the possible processes, some of which involve interactions with topography and larger-scale average velocities, as well as interactions among internal waves. Because most observations are limited to single passes with microstructure probes falling or being towed through an event, not enough information is obtained to distinguish among the possibilities. In a few locations where vertical mixing has scales of 10 m or more, acoustic backscattering yields images showing its evolution (Figure 1-5B), much like the returns from the high-resolution radars that follow billow evolution in the atmosphere. Development of imaging techniques for the smaller-scale events apparently common in the thermocline is urgently needed.

The function of salt fingers is another puzzle affecting thermocline dynamics. Salt

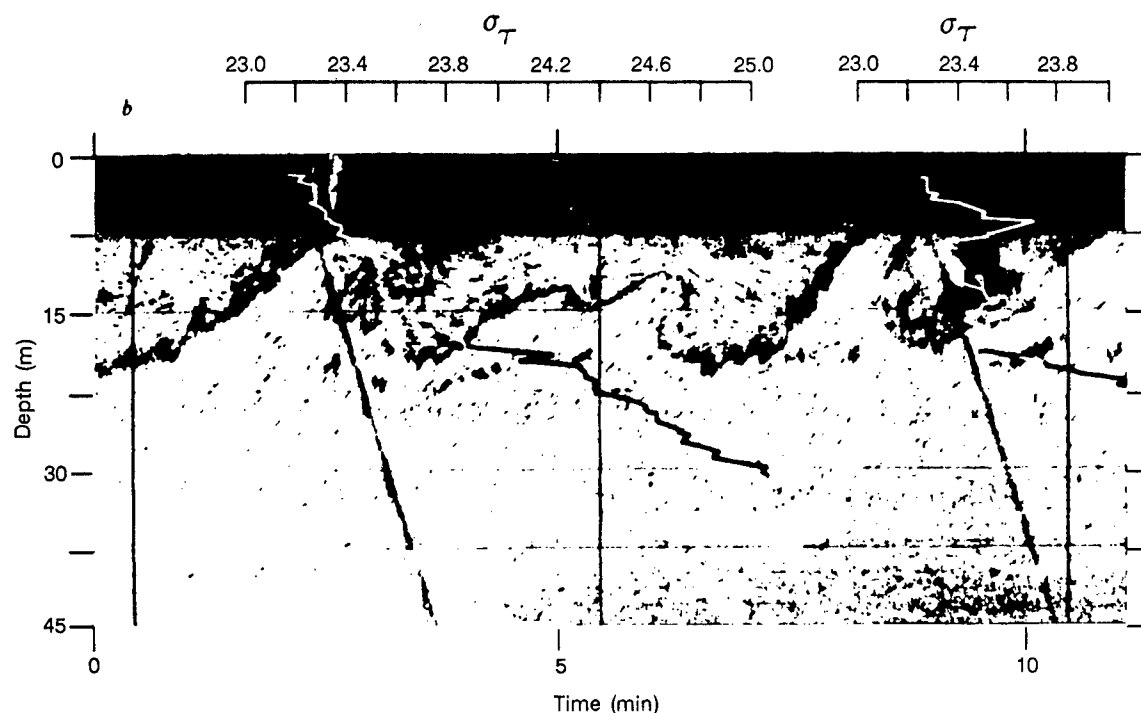


FIGURE 1-5B Acoustic backscatter imaging of a large, breaking internal wave. The diagonal lines show the passage of a density measuring instrument through the internal breaker; the density profile (jagged line) shows the unstable density field (Haury, et al., 1979).

fingers are centimeter-scale, alternating columns of rising and falling water propelled by the disparity in molecular diffusion rates of heat and salt. Thoroughly studied in the laboratory, salt fingers have been identified in only a few prominent oceanic locations (i.e., thermohaline staircases). Large volumes of mid-latitude thermoclines are diffusively unstable to fingering, but no direct evidence indicates that it is common. The first detailed observations in one of the thermohaline staircases, conducted during the Caribbean Sheets and Layers Transects (C-SALT), found surprisingly low mixing levels. If these results are typical, it is difficult to see how weaker salt fingers in typical thermoclines can have a significant function, but the issue is far from settled.

Turbulence measurements are likely to remain a very specialized kind of oceanic probing, severely restricted in scope relative to the scales of larger processes. Developing turbulence information applicable to the large scales hence requires parameterization in terms of large-scale variables. This need is now well recognized, and observations are under way to identify the mechanisms and dependencies linking these widely separated scales. The question of sufficient sampling is of equal importance and requires extensive testing of numerical models to determine the sensitivity of major aspects of large-scale processes to the mixing. Although much remains to be learned, the combination of laboratory experiments, numerical simulation, and oceanic observations is yielding rapid progress. A major advance would be the construction of a microstructure model like the one for internal waves that appeared in the early 1970s and spurred advances in that field. Figure 1-6 suggests that such a model may be possible.

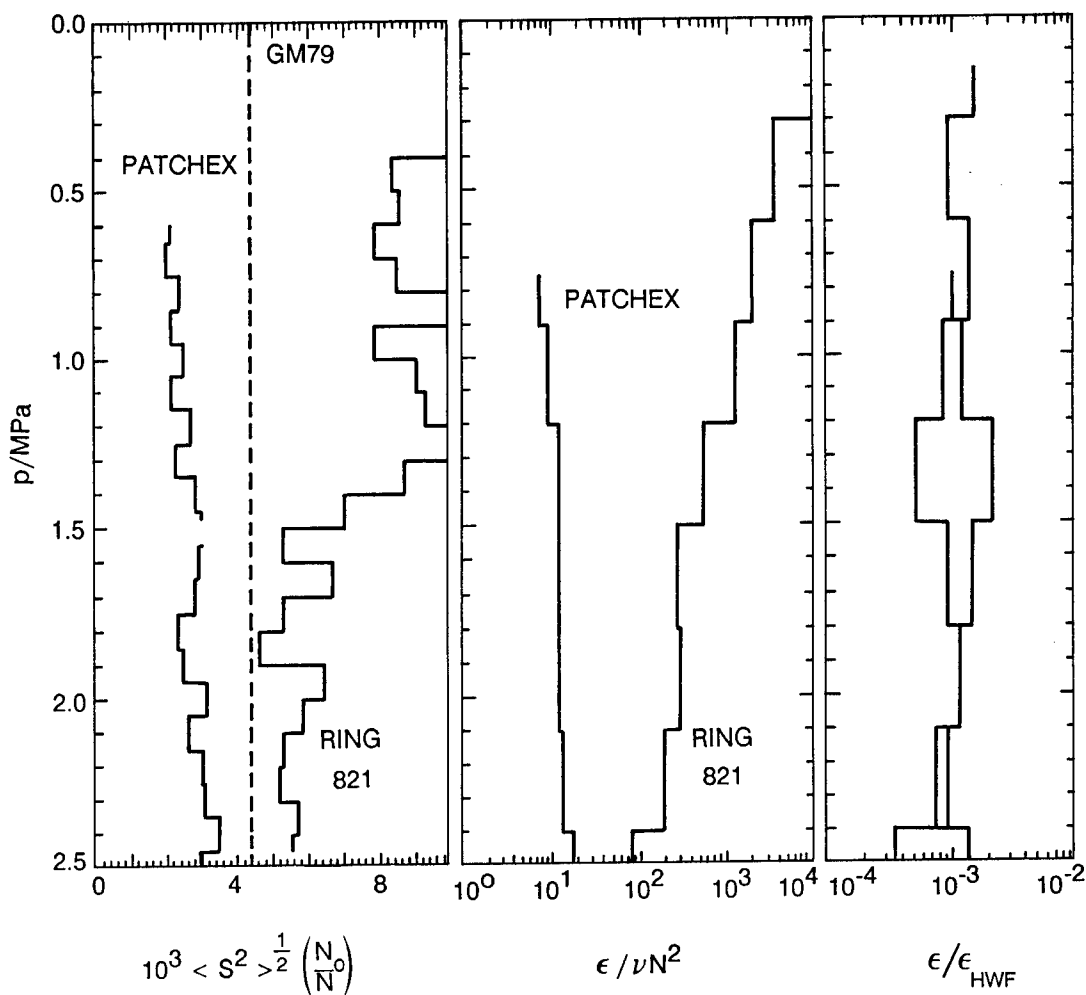


FIGURE 1-6 Turbulent dissipation rates, ϵ , in the upper thermocline scale with N , the stability frequency, and with the energy density of the internal wave spectrum. Two dissipation profiles are compared: Patchex, from the low activity region of the California Current, and Ring 821, from a warm-core Gulf Stream ring in January. The first panel compares the *root-mean-square shear* levels, scaled with N . The Patchex data demonstrate shear lower than expected from the Garrett and Munk (1975) internal wave model. Because the energy level, E , scales as S^2 , the difference in shear represents a very large contrast in internal wave levels. The middle panel contrasts dissipation rates normalized with νN^2 , which is a measure of the intensity of turbulence in stratified fluids. In the final panel the dissipation rates are normalized by $\epsilon_{HWF} \propto E^2 N^2$, suggested by Henyey, et al. (1986). Both N and E must be considered in scaling dissipation, as scaling by N alone (middle panel) is inadequate (Gregg, 1986, personal communication).

Upper Ocean Dynamics

Interactions with the atmosphere provide the ultimate driving force for most oceanic motions. Averaged over ocean basins and periods of years, the large-scale near-surface circulation reflects the prevailing winds, modified by continental boundaries and the earth's rotation. Warm water transported to the poles loses heat to the atmosphere, sinks, and spreads over the interior, forming the deep water of ocean basins. Fluctuations in the surface wind stress and heat flux occur over many space and time scales, forcing much of the

variability in the ocean. Studies of upper ocean dynamics seek to identify the mechanisms of these energy transfers, quantify their effectiveness, and model their behavior.

Significant progress during the past 10 years has resulted mostly from improvements in instrumentation that can operate in the difficult environment close to the sea surface. Better current meters and moorings extended to the surface permit air-sea interaction programs lasting for 2 years, instead of only one month. Reliable microstructure vehicles and acoustic Doppler sensing of near-surface water motion have yielded new insights about the mixing of heat and momentum down from the air-sea interface. New techniques just coming into use promise further observations that will motivate upper-ocean research and fuel new theoretical and numerical modeling studies. For example, helium-tritium dating of water on constant-density surfaces in the eastern North Atlantic (Figure 1-2) demonstrates movement from the upper ocean into the interior. These measurements have stimulated new interest in more realistic modeling and observations of the mechanisms by which the atmosphere drives the interior, via the upper ocean.

In 1977 the Mixed Layer Dynamics Experiment (MILE) kept two ships and three surface moorings at Ocean Station Papa (50°N , 145°W) for 19 days. An ambitious effort for its time, MILE combined several newly developed techniques for measuring the upper ocean. Vector measuring current meters (VMCMs) on the moorings provided the first accurate measurements of small mean currents in the presence of surface waves. A towed thermistor chain and a depth-cycling conductivity-temperature-depth (CTD) profiler mapped scalar fields from scales of tens of kilometers to meters. Free-fall and towed microstructure vehicles observed turbulence in the surface mixed layer and upper thermocline.

Similar suites of measurements have been used in all subsequent upper-ocean experiments. In 1978 the Joint Air-Sea Interaction Project (JASIN) was a large international field program in the Rockall Trough between Scotland and Iceland. The moorings were kept in place for 46 days, and an international flotilla of 14 ships shared the effort to maintain station for most of this time.

Owing to their limited duration, MILE and JASIN captured only a small number of forcing events. The short times are dictated by the need to obtain measurements of high-frequency processes, especially internal waves and turbulence, requiring manned platforms or moorings with high-frequency recording. By the early 1980s, the desire to capture a long time series of forcing and response led to the development of surface moorings and current meters capable of 6-month and longer deployments. They were used in studies of the equatorial Pacific and the mid-latitude Atlantic, where the Long-Term Upper Ocean Study (LOTUS) yielded a 2-year time series. Following these successes, arrays of moorings have been maintained for extended periods. For example, the Frontal Air-Sea Interaction Experiment (FASINEX) deployed a nine-mooring array across an upper-ocean front for 6 months to observe frontal modulation of air-sea interactions in both the ocean and atmosphere. Using the low-frequency observations provided by these long-term measurements as background, ships converged for several weeks near the moorings for intensive sampling of the high-frequency processes. Using aircraft with expendable current profilers (XCPs) is an even more recent advance, allowing measurements of small-scale energy under conditions too severe for ship observations. Successful observations have been made in hurricanes.

Much has been learned from these cooperative programs. The first realistic description of the wind-induced Langmuir circulation has revealed a cellular circulation of surprising intensity, with speeds up to 30 cm/s (see Figure 1-7). For as yet unknown reasons, the cells and the downwind surface jet are oriented about 15° to the right of the wind. Microstructure observations yielded parameterizations of turbulence for cases forced by wind stress and

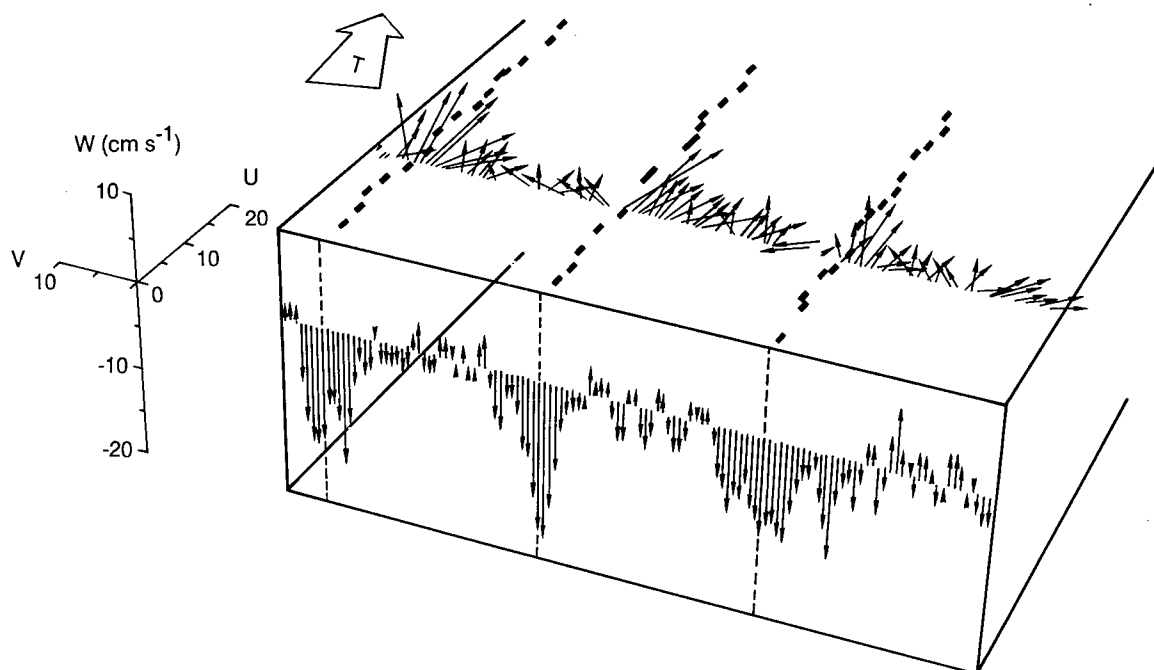


FIGURE 1-7 Time series of vertical and horizontal velocities showing Langmuir circulation in the upper ocean. The three-dimensional plot displays horizontal velocity vectors at 23 m depth, with time increasing to the right; 30 minutes of data are plotted. The vertical velocities at 23 m are plotted every 14 seconds. The black rectangles simulate computer cards floating on the surface in the convergence lines of the three-dimensional circulation pattern (Weller, et al., 1985).

for those driven by convection. As outlined in the discussion of equatorial oceanography, diurnal convective forcing plays a major role in the dynamics of the equatorial undercurrent.

In spite of the rapid progress, the great complexity of upper-ocean dynamics and air-sea interactions leaves far more unknown than known. Among the puzzles are the following.

- Key elements of the forcing of the upper ocean by the atmosphere remain poorly known. Precipitation is measured only rarely, and relative humidity and long-wave radiation are difficult to obtain reliably and accurately. The recent Storm Response Experiment (STREX) indicates a factor of three change in the momentum transfer due to interactions of the wind velocity and surface waves; this dynamic coupling is not included in the bulk transfer coefficients currently used to compute the fluxes. In view of these crude estimates of the forcing, measurement of some responses of the upper ocean exceeds specification of the meteorological forcing. A new Office of Naval Research (ONR) ARI on Surface Wave Processes should solve some of these problems but is only a tentative first examination of the full physics of the upper 5 to 10 m of the ocean.

- Mid-latitude convection, particularly along the Gulf Stream and Kuroshio, forms deep mixed layers that appear to ventilate much of the upper thermocline in the subtropical gyres. High-latitude convection forms deep chimneys that supply much of the deep and bottom water. Although some progress has been made in parameterizing turbulence produced in convectively driven surface mixed layers, little is known about the full three-dimensional processes involved, let alone how to model them.

- Many mechanisms appear to permit fluctuations in wind stress to supply energy to the oceanic internal wave field, and numerical simulations provide estimates of the energy

fluxes needed to sustain the average observed internal wave levels. Nevertheless, very little is known about which mechanisms are effective. These fluxes to the internal waves may be important energy sinks for the upper ocean, and they are the principal energy source for internal waves. In the thermocline, mixing studies are exploring the dissipation of internal wave energy. The absence of similar progress with the sources prohibits development of a comprehensive understanding of internal waves.

Equatorial Oceanography

Major weather and oceanic disturbances in locations seemingly as disparate as Australia, South America, and North America accompanied the uncommonly strong 1982-1983 El Niño. Widespread coverage in news media made apparent to the public the growing recognition among oceanographers and meteorologists of the global effects of equatorial ocean-atmosphere interactions. Intense observations and modeling programs designed to study these phenomena are yielding important progress in many of the complex and interrelated processes involved, most recently in small-scale vertical mixing, equatorially trapped waves, interactions with western boundary currents, and the adjustments of ocean basins to equatorial forcing.

Basin-scale adjustments to changes in forcing over tropical oceans are well known and distinguish low- from middle- and high-latitude oceans. These adjustments are both seasonal and interannual. The former were the focus of SEQUAL/FOCAL, two major programs in the equatorial Atlantic. The 1982-1983 El Niño is the most conspicuous example in this century of an interannual adjustment. Because this event came at an unexpected time in the seasonal cycle, without the preconditioning previously thought necessary, it has already altered the conventional scenario.

Observations of the huge 1982-1983 El Niño event were made by routine sampling programs and by serendipity, rather than by specific measurements dedicated to following its unpredicted course. Subsequent understanding has increased sufficiently to produce an *a priori* prediction of the relatively mild 1986-1987 El Niño-like warming, based on several approaches including a coupled atmosphere-ocean dynamic-thermodynamic model, a statistical model, and a kinematic internal wave model. Advances in numerical models now permit their operational use to monitor basin-wide adjustments in the Pacific, rather than confining them to hindcasting.

Equatorially trapped waves have been observed in a variety of situations over the last decade, before which their existence was only theoretically proposed. The four possible classes of wave motion (gravity, Rossby, mixed Rossby-gravity, and Kelvin) have now all been identified. The spectrum of these waves is not well known, nor have regional, seasonal, other intra-annual, or interannual variations been delineated.

The propagation speeds of equatorially trapped, long Rossby waves and Kelvin waves cause a large-scale oceanic response to changes in wind forcing that is much faster near the equator than at midlatitudes. Generation of equatorial Kelvin waves by wind has been observed, but the efficiency of excitation is not established. In addition, propagation of waves through the equatorial current field is observed but poorly understood.

As the main conduits for poleward transport of warm equatorial water, western boundary currents have long been a focus of research in the Indian Ocean. Recent measurements and modeling of the Somali Current, moving northward offshore of eastern Africa, reveal a complex evolution through the onset of the monsoon. Models can now reproduce many of these features. More recently, western boundary currents are receiving renewed attention in the Atlantic and Pacific as well. Work similar to that in the Indian Ocean is planned in

the tropical western Atlantic, where the north Brazil Current alternately feeds the North Equatorial Countercurrent offshore and the Guiana Current inshore.

Owing to the absence or weakness of the Coriolis force in the equatorial ocean, small-scale vertical mixing must balance the large-scale horizontal pressure gradients forcing currents. Intensive microstructure measurements during the Tropic Heat Program revealed that the enhanced turbulence may extend much further off the equator than previously thought. Moreover, much of the turbulence is dominated by diurnal fluctuations driven by the surface cycle of heating and cooling, but reaching much deeper into the thermocline than is found in similar cycles at mid-latitudes. Internal waves produced by convection in the surface layer have been proposed as the origin of the strong nighttime mixing, but definitive evidence is lacking.

Parameterization of small-scale mixing is necessary to incorporate its effects into numerical models. For the first time, a parameterization based on measurements has been attempted, based on data collected during the Tropic Heat Programs. The generality of these results, even on the equator, has yet to be established.

Long-period oscillations and deep jets are phenomena peculiar to the equator. Poorly understood, they seem to be intimately tied to the large-scale energetics. Energetic oscillations, particularly in the north-south flow, grow and decay seasonally. Various known as long-period, 21-day, 30-day, or instability waves, these features mix heat and zonal momentum effectively and are important links in the overall circulation. Numerical models have reproduced similar waves as instabilities to both the meridional and vertical shear of zonal currents.

Deep jets occur as zonal flows with vertical scales of roughly 100 m. Confined to the equator, their behavior is curious, as they exist for up to 2 years without vertical propagation.

Many pieces of the equatorial puzzle have been found. Vertical mixing is better defined near the equator than at mid-latitudes and parameterizations are emerging. Strong large-scale fluctuations having periods of 2 to 4 weeks are understood to be important agents in mixing heat and momentum horizontally. The reality of the equatorial wave guide is firmly established, but major questions remain about propagation dynamics. Increasingly comprehensive observations are allowing far more realistic modeling; useful forecasts are the goal. Much of the impetus now comes from the decade-long international Tropic Ocean/Global Atmosphere (TOGA) Program, which began in 1985. Although past attention centered on the more accessible phenomena in the upper ocean, future efforts will turn deeper to address the problems of meridional transport of mass and heat relevant to the mid-latitude general circulation. In addition to a more complete understanding of known phenomena, these initiatives promise discoveries of the unexpected, like the deep jets, long-period oscillations, and undercurrent.

NAVAL RELEVANCE

Napoleon's maxim of war was "know your terrain." In today's world, the Navy must know its unique "terrain" of eddies, fronts, and seamounts just as Napoleon's marshals needed to know the hills, streams, and forests of the battlefield.

Knowledge of the oceanic environment is particularly critical in ASW the Navy's prime warfare area. Given its global mission, the Navy ideally requires nowcasts and forecasts for the world's oceans on spatial scales from meters to thousands of kilometers and temporal scales of seconds to years. Because this goal is clearly unattainable, the Navy must define a set of nested requirements that in sum satisfy both strategic and tactical needs.

Global ocean numerical modeling on eddy-resolving grid scales will, for example, improve the utility of long-range, low-frequency acoustic systems of the future. To be most useful, such models must be capable of being updated in near-real time using a variety of inputs, principally from satellite sensors, but including a small number of in situ sensors.

The prosecution of a single target, however, dramatically shifts the scales of interest to the mesoscale and small-scale domain. Here, the global model may only provide predictions of smoothed mixed layer depth and the approximate location of large-scale fronts. Within this context, a successful prosecution may depend critically on knowing the structure and detailed location of a particular front or the occurrence, size, and shape of turbulent patches. Models of the local environment could range from a numerical model on a ship's or aircraft's computer to a conceptual model in the mind of a trained operator. Both require an appropriate understanding of the physics of the real ocean; the Navy looks to basic research in physical oceanography to provide this understanding.

The congruence of Navy interests and physical oceanographic research spans all missions and warfare areas. The advent of satellite-based scatterometers, altimeters, and radars, especially synthetic aperture radars whose resolution is theoretically independent of altitude, offers the prospect of continuous global mapping of the wind and wave field at the ocean surface, the mesoscale circulation of the upper ocean, and the extent of ice cover in polar regions. Measurements such as these have immediate application for the optimal routing of ships and aircraft for safety, for fuel efficiency, and for the most effective tactical exploitation of oceanic fronts and eddies. Acoustic tomography is an extremely promising tool for probing the structure of large segments of the ocean; in turn, this line of research may lead to a significant improvement in the performance of long-range surveillance systems.

Numerous additional examples can be offered, but it should be clear that naval operational relevance and physical oceanography are almost synonymous. The physical ocean, including the lower atmosphere above the sea surface, influences every aspect of naval operations, from strategic planning to the design and ultimate tactical application of platforms and sensors. Physical oceanography is thus the cornerstone of Navy-related environmental research and deserves a continued strong emphasis in keeping with its importance to the operational Navy.

In contrast to other fields in which the impact of research on naval operations is indirect, progress in physical oceanography can often have immediate applicability, and the relationship between research and tactical operations can be mutually beneficial. This synergism is particularly important in ASW, where exploitation of the ocean's physical properties (such as acoustics) is the essence of operational success.

CURRENT PROGRAMS

The physical oceanography program is the largest program in the ONR, supporting roughly \$20M of basic research in all areas of physical oceanography. The objectives of the program are to develop a comprehensive research effort on physical oceanographic phenomena on time and space scales of naval relevance, and to marshall a broad cadre of academic oceanographers focused on specific Navy issues as they arise. The program emphasizes the fundamental understanding of complex interactive physical processes with the goal of reliable modeling and prediction.

The program recognizes that high-quality field observations are the basis of new insights and are the truth against which models and predictions must be developed and tested. Therefore, physical oceanographic field observations and experiments are the most

important and expensive parts of the program. The panel notes that satellite remote sensing gives a global view of the ocean, and supercomputers promise an integration of global views and powerful models, but for the foreseeable future these new tools only heighten the requirement for high-quality field measurements. Remote sensing, for example, tends more to reveal new, unexplored, and unanticipated phenomena, than to answer existing questions about the ocean. A photograph from the Space Shuttle may reveal interesting new patterns on the surface, but it is people on ships who will explain and perhaps exploit those patterns.

An objective of the program, therefore, is to learn how to blend the remote, superficial, and low-resolution but global views of the ocean with in situ, full-depth, high-quality but sparse data obtained from ships, buoys, and drifters. Two of the three university research initiatives (URIs) that augment this program are, in fact, focused strongly on this issue.

ACCELERATED RESEARCH INITIATIVES

Two ARIs have already been completed in the physical oceanography program, Upper Ocean Variability (ended in FY 1985) and Remote Sensing (ended in FY 1986); the latter was a joint program with Coastal Sciences.

The current ARIs are in Air-Sea Interactions, Southern Oceans (joint with Marine Geology and Geophysics), and Fine-Scale Variability (all started in FY 1984), and Synoptic Ocean Prediction (started in FY 1985). Examples of some major field programs under these ARIs, respectively, are:

- FASINEX (1986): to study air-sea interactions in the vicinity of the subtropical convergence zone front in the western North Atlantic.
- AGULHAS (1986-1987): to study the eddy, and heat transport dynamics of the Agulhas Current retroflexion region South Africa.
- PATCHEX (1986): to examine the relationship of internal waves and mixing west of the California Current.
- SYNOP (1987-1988): to study in detail the dynamical balances of the Gulf Stream system, with an eye toward improved prediction models.

Two ARIs starting in FY 1988 have been using core support to phase them in. They are Arctic Oceanography (joint with Oceanic Biology and with the arctic program itself) and Surface Wave Processes. The latter is planned with two field programs during 1990-1991; one is oriented toward the improved prediction of directional wave spectra and the other focused on what it is that surface waves do (like break and provide turbulence) to the upper ocean.

One additional ARI—Topographical Interactions—will begin in FY 1989; it will focus on the effects of abrupt topography (e.g., seamounts, continental shelf edges) on physical, biological, and sedimentary processes in the vicinity. The science program has not yet been fully structured.

FUTURE PROGRAMS

Interactions and Modeling of Mesoscale and Submesoscale Processes

Because the mesoscale contains most of the ocean's kinetic energy, determining the major dynamics of 100- to 200-km scales is essential to a first-order description of the ocean. The only test of such understanding is developing numerical models that accurately simulate observations. Owing to the strong acoustic signature of mesoscale features, the Navy is now testing mesoscale models for use at sea, in real time.

Preliminary model studies show that the mesoscale eddy strength is directly related to the small-scale diffusivities introduced for reasons of numerical stability or for parameterizing (albeit inaccurately) observations of small-scale mixing (M. Cox, personal communication). Observationally, the dissipative phenomena of the ocean mesoscale are not known (except for bottom friction) but strongly govern the eddy climate of a model. A conceptual, experimental, and modeling basis is required for submesoscale and mesoscale interactions, including thermodynamically active eddy fields, where both heat and salt are allowed to have different sources and where eddies produce the horizontal mixing and water masses. The transition from quasi-geostrophic models of an eddy-resolved ocean to one in which the thermocline evolves together with the eddies is imperceptibly slow in both the applied and the basic research community.

Although some "community modeling" efforts have agreed to try and examine large-scale models, what is also needed—and is ripe for exploitation—is a community modeling effort on the meso- and smaller-scale processes. The computational power and some scientific interest exists, but the topic needs aggressive leadership.

Horizontal and Vertical Mixing in the Mid-Ocean and Near Its Edges

Western boundary current areas have been most intensely surveyed for eddy activity, and the eddy role in the circulation processes is best understood there. The mid-ocean eddy field, in comparison, is undersampled; its role in vertical and horizontal mixing, mean circulation, and the physical processes that establish the main thermocline is not known. Whether the subtropical thermocline is driven at its edges (as subduction and homogenization theorists would have it) or it is locally established (as vertical mixing geochemists believe) cannot be understood without a better understanding of the horizontal eddy mixing processes in the mid-ocean.

The major flux balances responsible for the formation of the main thermocline remain uncertain. One class of models neglects fluxes due to internal waves and small-scale mixing, assuming that lateral advection with a small but significant vertical mixing component is the dominant process. Another group of models, favored by geochemists, relies on small-scale turbulence as the dominant process. Sorting it out is one of the most important tasks of physical oceanography. The information is also essential for improving the meso- and large-scale models run by the Navy and for understanding the time and space scales that affect both acoustic and nonacoustic ASW. This topic is complementary to the previous topic and represents the observations and physics that would need to be incorporated in the meso- and smaller-scale modeling efforts.

Simultaneous measurements of internal waves and turbulence, chemical tracers, and horizontal advection are needed. Major improvements in numerical modeling are required to evaluate nonturbulent vertical transport produced by the combined effects of horizontal advection and small nonlinearities in the vertical gradient in density of seawater. The scope of the problem is much larger than can be attacked in a fixed-duration effort like the ARIs. Tracer measurements are planned for the WOCE Core 3 effort, but it is already clear that the resources available to WOCE will be inadequate to measure small-scale processes at the same time with the accuracy needed. An ONR effort in cooperation with WOCE would be a direct extension of previous ONR-funded programs that have concentrated on structures and processes relevant to ASW.

Near-Surface Physics and Air-Sea Fluxes

Inadequate observations of the upper 5 m of the ocean limit the accuracy of calculations of air-sea fluxes. Current meter data usually become available at 10 m, and sometimes at 5 m. Finding better data in this region is unlikely without a concerted effort. Downward-looking acoustic Doppler profilers may be used more often in the future, but due to surface reflections of side lobes, data from near the surface have not been useful. What are shear levels in this region? If they are large, then previous efforts at momentum balances based on current meter data from 5 m and deeper are suspect. Do breaking surface waves inject fluid from near the surface into the region below and thus play a role in mixing? Do they contribute momentum? Is there a wave-driven component of the surface drift current? Considerable insight into how the ocean responds to atmospheric forcing would be gained by an effort to address the physics of the near-surface region. This is also the region that underlies the surface film and microlayer efforts of the Biology and Chemistry programs.

The basic observational goal should be accurate specification of all components of the air-sea fluxes of heat, mass, and momentum. The rationale is that better understanding of upper ocean dynamics and the ability to model and predict the upper ocean environment and the coupled, global atmosphere-ocean system depends on accurate observation and specification of the meteorological forcing fields. It has been apparent for some time that knowledge of the buoyancy flux as well as the momentum flux is needed to specify near-surface thermal structure. Improved air-sea flux calculations on a global basis will greatly enhance our ability to determine how the interactions drive the ocean. This may also be an area that could benefit from proposed WOCE programs in the surface layer.

Deep Convection

During strong cooling events, the heat loss from the ocean is between 1000 and 2000 W/m², causing the ocean surface to steam like a cup of hot coffee on a cold day. (By comparison, the heat gain under the noon equatorial sun is about 1000 W/m². Sustained cooling at high latitudes penetrates hundreds to thousands of meters below the surface. Slow equatorward spreading then transforms these "chimneys" of cold, dense water into the intermediate and bottom water of the world ocean.

Other than a general notion that deep convection occurs in distinct columns several kilometers in diameter, too little is known about deep convection to describe even the basic force or flux balances. The topic has great scientific relevance in arctic areas of high naval interest. A coordinated program of observations and modeling is needed to produce the first description of the scales and mechanisms responsible for forming a large fraction of the ocean's volume. An understanding of the structures and processes in one of the Navy's prime submarine operating areas has strong naval relevance and is of basic importance to oceanography.

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2

Coastal Sciences

Coastal oceanography is the study of those oceanic phenomena and processes that are strongly influenced by the lateral (coastal) boundary or related topography (ranging from the beach to the outer continental margin). Recently studied topics in coastal physical oceanography include wave-driven coastal upwelling and associated offshore filaments, coastal fronts, coastally-trapped waves, flow in straits and tidal channels, and wind- and buoyancy-driven flows in marginal seas. The dynamics governing these physical phenomena clearly depend on the coastal boundary and shape of the adjacent ocean bottom.

Although many biological, geological, and chemical research areas in coastal oceanography have applications to naval operations, this review will focus on physical phenomena and processes. The reasons are several. First, recent progress in coastal physical oceanography promises to lead to important new studies within this subdiscipline. Second, since most of the dominant biological, chemical, and sedimentary processes depend critically on the physical environment, especially the flow field, a better understanding of physical processes is essential for developing new understanding and predictive capability for all aspects of the coastal ocean. Finally, the ONR Coastal Sciences Program was redirected in 1982 to emphasize coastal physical oceanography. In part, this decision was based on an assessment that limited program funding required a narrowing of scope to be most effective. The panel notes, however, that coastal oceanography is inherently a multidisciplinary field, and a number of research problems with high relevance to naval operations cannot be addressed in the present program format. For this reason, the panel encourages ONR to consider expanding the scope of the Coastal Sciences Program, either through augmented funding or a realignment of existing programs, to achieve meaningful advances in multidisciplinary problems. Excellent combinations of biology, chemistry, and physics exist in the Coastal Transition Zone ARI, but a number of multidisciplinary problems require a long-term commitment that is more appropriately provided within a core program.

TRENDS AND PROGRESS

Coastal physical oceanography includes an assortment of processes that covers a broad range of space and time scales and geographic locations; their commonality is that all the processes depend in a significant way on the interactions with the bottom or lateral boundary

of the ocean. Significant advances have been made recently in understanding several research topics: mean flow generated by breaking waves on beaches, coastally trapped waves on both beaches and shelves, turbulent processes in the coastal ocean, strait dynamics, upwelling filaments, marginal seas, the estimation of dynamical and heat balances, steady flow over the mid shelf, and processes at the shelf-break front, to mention a few. Discussion will be limited to only a few items because they span a diversity of processes and represent different levels of development.

Modeling Mean Flow Generation by Breaking Waves on Beaches

Steady alongshore currents are generated when obliquely incident wind waves shoal and break on a beach and can cause alongshore sediment transport. The steady component of the wind wave momentum field (known as the wave "radiation stress") is transferred to the mean flow field during breaking. At steady state, radiation stresses that drive the mean flow are balanced by bottom drag. In most alongshore current models, all incident wind waves have the same height and period, and break at the same offshore location. This modeling assumption results in a discontinuous alongshore current; the current is maximal at the break point and zero seaward of this position. Most models smooth this unrealistic discontinuity by including eddy viscosity. In a newly developed model, the stochastic, random nature of wind waves results in initial breaking, which is spatially distributed rather than fixed in location. Resulting alongshore currents vary gradually and the need for a physically unrealistic eddy viscosity is eliminated. This new model has been verified by comparison with field observations with particularly simple incident wind wave fields.

Observations show that surf-zone alongshore currents occur with a variety of incident wave conditions, including cases in which locally generated seas and swells from a distant storm approached the beach from different quadrants. No models exist for alongshore currents in this situation because no models describe how the breaking process alters a complex wave directional spectrum. The strong shears and reversals of the alongshore current that could conceivably occur in this circumstance were not observed. A decomposition of the mean alongshore current pattern with the aid of empirical orthogonal function (EOF) in one recent experiment shows that most (>90 percent) of the current spatial variation is described by a classic parabola (Figure 2-1) and that temporal variation of the current strength is highly correlated with total (frequency-integrated) radiation stress. Surf-zone alongshore currents apparently are sensitive primarily to total radiation stress, and are influenced little by the details of the radiation stress spectrum.

Surf Beat

Many recent field observations show that fluid motions in the inner surf (or "breaker") zone are dominated by fluctuations with periods of a few minutes (Figure 2-2). These low-frequency motions, also known as "surf beat" or "infragravity waves," are believed to provide a major erosive force during storms; surface-beat, root-mean-squared velocities of 150 cm/s have been reported. Because of their relatively low frequency and long wavelength, these waves can become very energetic before a critical steepness is reached and additional energy input is dissipated by wave breaking. Alongshore arrays of current meters have been used to determine the alongshore wave number structure of surf beat at two California beaches (Figure 2-3).

Surf beat is evidence that low-frequency variations in near-shore surface elevation are related to the incident wave field and to the alongshore and cross-shore topography. Edge

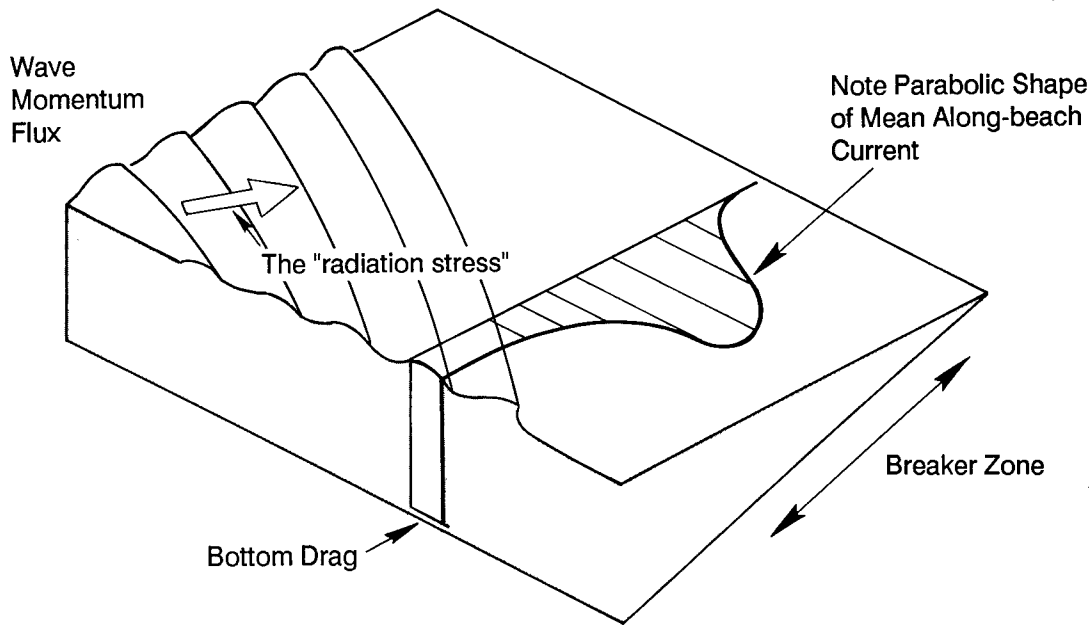


FIGURE 2-1 Mean alongshore current generation by breaking waves (Beardsley, 1987, personal communication).

waves are trapped in shallow water and contribute to surf beat. Edge waves also have a particular relationship between frequency and wave number so that their contribution to surf beat can be quantified by space-time spectral analysis. In a recent study, for all cases analyzed, between 42 and 88 percent of the alongshore current variance at the array was contributed by low-mode ($n \leq 2$) edge waves (Figure 2-3). The low-mode signal in the cross-shore velocity at the array was usually masked by unresolvable high-mode and/or leaky waves, since less than 35 percent of the cross-shore current variance was due to low-mode edge waves. In some cases, the spectrum of swash motions on the beach face (which is an estimate of the one-dimensional infragravity shoreline elevation spectrum) was measured and compared to the edge-wave shoreline elevation variances inferred from the velocity measurements at the array. As much as half of the variance in the shoreline-swash spectrum is estimated to be contributed by low-mode ($n \leq 2$) edge waves. Thus, low-mode edge waves can contribute significantly to both the alongshore velocity and run-up components of the nearshore infragravity wave field. The generation mechanism of these edge waves is not known, and about all that can be said about the cross-shore surf beat velocity field is that it is dominated by motions with alongshore length scales greater than 500 m.

Subinertial Coastally Trapped Waves

Coastally trapped waves, a class of low-frequency fluctuations (with periods greater than the local inertial period) that propagate with the coast on the right (left) in the Northern (Southern) Hemisphere, provide a very useful framework for models of large-scale, wind-driven current fluctuations on the continental shelf and slope. The waves are trapped because the lateral forces caused by the earth's rotation are balanced by the pressure forces of the lateral boundary.

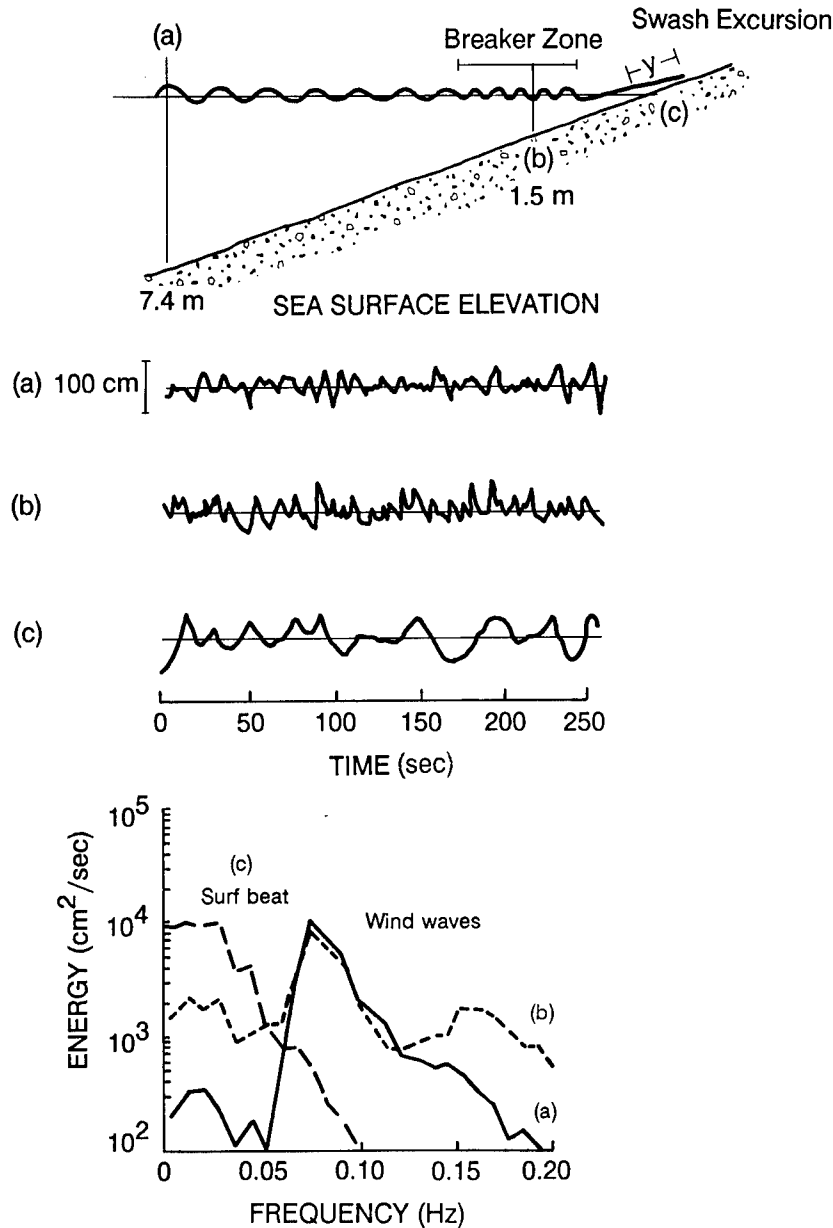


FIGURE 2-2 Sea surface elevation time series and energy spectra (a) well outside the breaker (surf) zone (736 cm depth), (b) in the breaking region (153 cm depth), and (c) on the beach face (swash excursions, 0 cm depth). The spatial differences in the temporal character of the sea-surface elevation, especially the shift in energy from the incident wave field to lower-frequency surf-beat at the shore, are evident (Guza, 1985, personal communication).

The theory of coastally trapped waves has proved extremely successful, both for hind-casting pressure and alongshore current fluctuations and for providing a clear conceptual understanding of this class of motions. Because of the theory's large-scale focus, it does not yield useful information about density and cross-shore current changes.

Recent research in coastal-trapped wave processes has focused on comprehensive comparisons with field observations from the Australian Coastal Experiment (ACE) and the

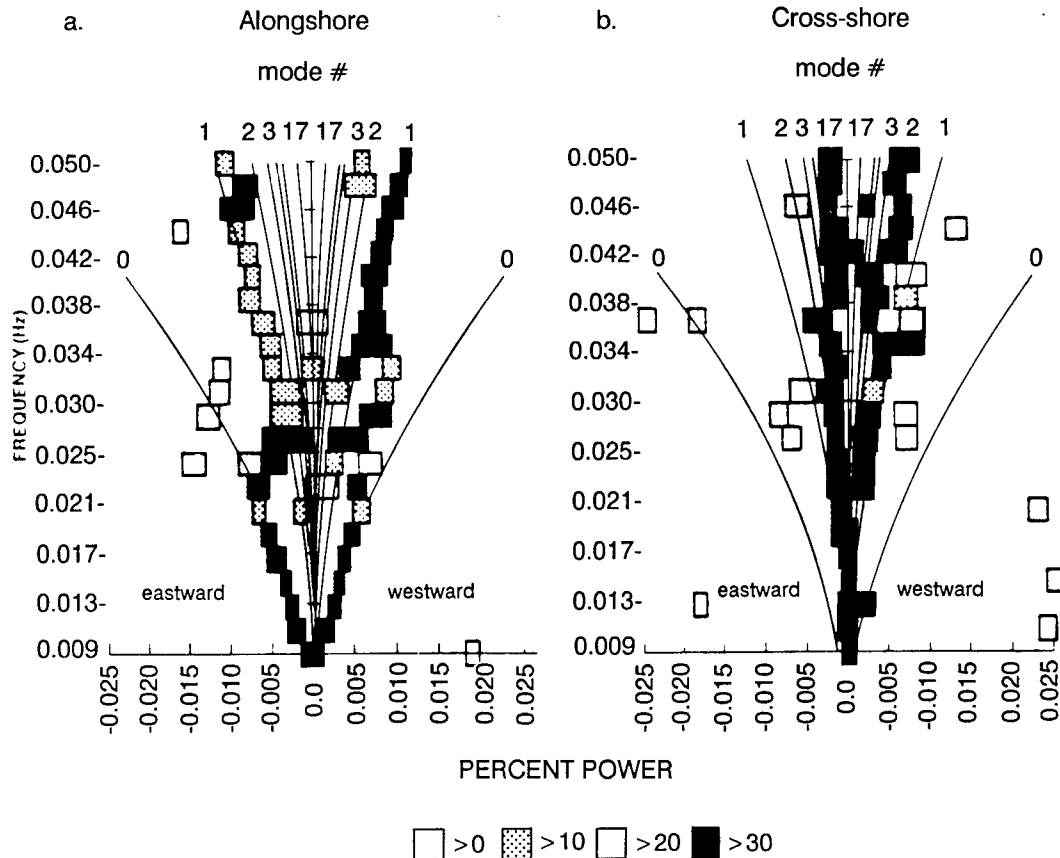


FIGURE 2-3 The (a) alongshore and (b) cross-shore current wave number frequency spectra (DOF = 42) on 14 February 1980 at Santa Barbara. The first four and cutoff mode (17) edge wave dispersion lines are shown. The rectangular boxes mark the location of energy peaks defined as those wave number maxima that have an adjacent valley below their half power. The wave number width of each box is the half power bandwidth of the peak. The shading density indicates the percent power in the frequency bin that lies within that half-power bandwidth of the peak. Note that the alongshore current spectrum is dominated by the lowest free edge wave modes $n \leq 2$ while most of the cross-shore current variance is caused by higher modes (Oltman-Shay and Guza, 1987).

Coastal Ocean Dynamics Experiment (CODE) and Super CODE experiments, and with development of stochastic approaches to forced wave modeling. The field comparisons show that the theory correctly simulates the temporal behavior of the alongshore current over much of the shelf but systematically underpredicts its amplitude (see Figure 2-4). The overall success of the theory has, however, brought it to a point where many of its leading practitioners are beginning to seek different avenues.

Turbulent Processes

Turbulent processes in the coastal ocean are now receiving increased attention in the water column, near the bottom, and near the surface. In the water column some spectacular strides have been made in appreciating the importance of mixing due to current shears. For example, researchers have found that breaking internal waves over the Scotian shelf contribute energy to mixing processes in amounts comparable to that provided by the

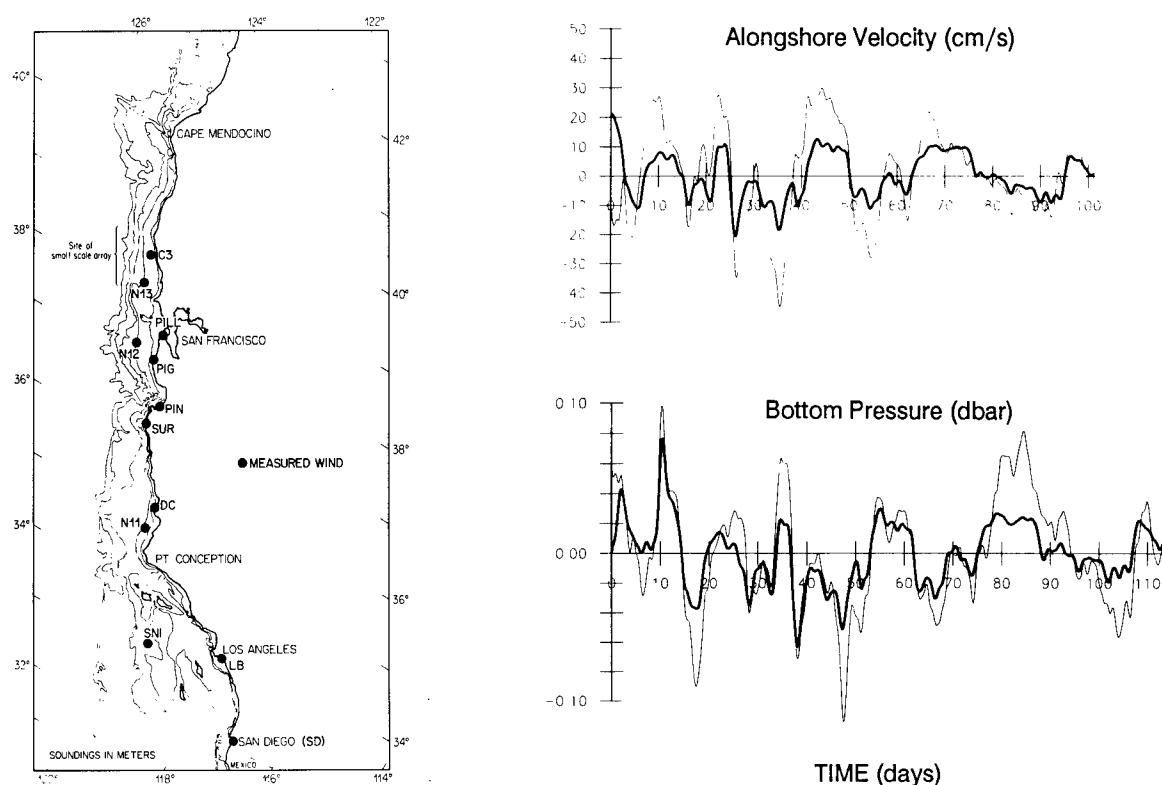


FIGURE 2-4 Comparison of observed (thin) and predicted (thick) alongshore velocity (upper panel) and bottom pressure (lower panel) time series based on the wind-forced, coastal-trapped wave model. The velocity measurements were made at 55 m depth at a midshelf site located on the 90-m isobath off northern California starting on 1 April 1982, and extended through the spring and summer upwelling season (see insert map). The model input included wind stress estimates based on coastal and buoy winds measured along the California shelf north of San Diego. The correlation coefficients between the predicted and observed time series shown are 0.75 and 0.81 for the velocity and bottom pressure, respectively. Both variables are underpredicted by a factor of 1.6 (Chapman, 1987).

surface wind stress. Turbulence induced by the breaking of short, high-frequency internal waves derived from internal tides has also been shown to lead to unanticipatedly large energy dissipation, both in the Gulf of California and in the Strait of Gibraltar (see Figure 2-5). Such advances have used both conventional CTDs and new state-of-the-art instrumentation such as an advanced microstructure profiler (AMP) to obtain high-resolution profiles of water structure variability.

Understanding of the bottom boundary layer over the shelf has significantly improved in the last decade. Novel instrumentation has demonstrated nonlinear coupling of high-frequency surface waves and low-frequency flows in the bottom boundary layer, which has led to a rationalization of previous high estimates of bottom drag over the shelf. Further, the inclusion of more realistic bottom stress changes the calculated wind-driven flow field over the continental shelf. Wave-current interaction models promise improved accuracy and understanding of the bottom boundary layer over the shelf, although there are many more theoretical and experimental challenges to be overcome before this promise is fulfilled. These models further point out the need for improved predictive models and overall understanding of the surface wave climate over the shelf, since this forcing is a crucial model input.

AMP Gibraltar Cruise
18 Oct 1985 - Gibraltar Section

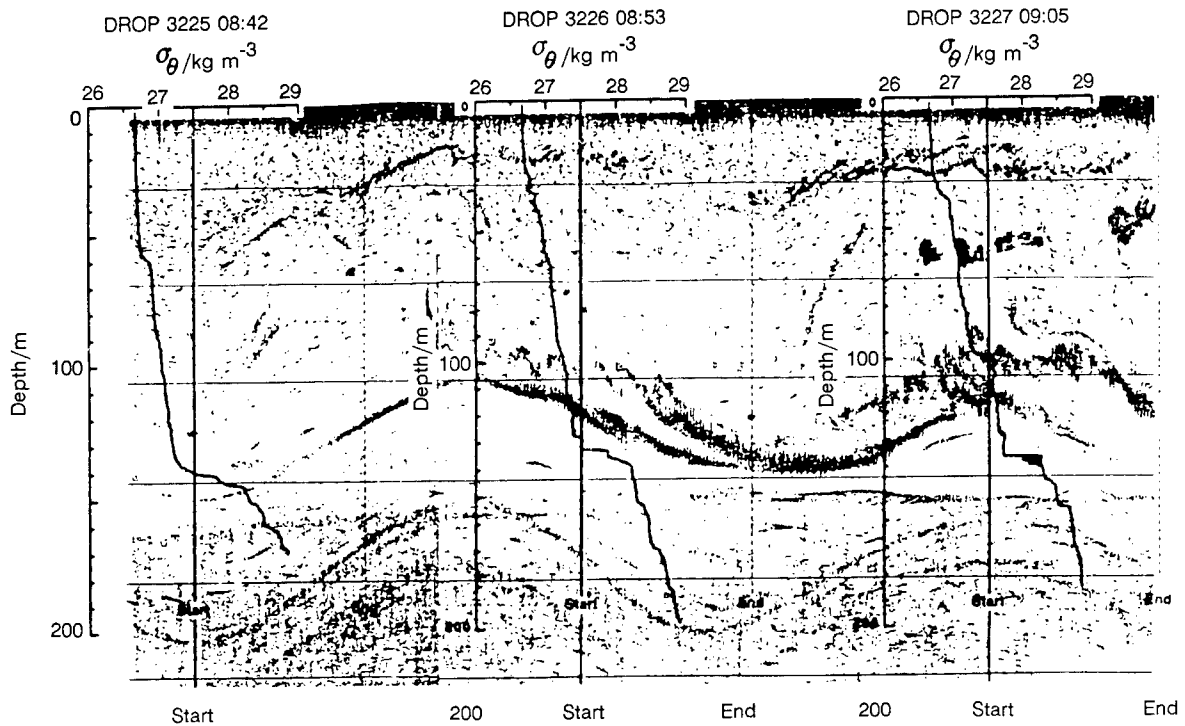


FIGURE 2-5 A composite view showing three advanced microstructure profiler (AMP) density profiles overlaid on an echosounder image of the water column obtained just west of the Strait of Gibraltar. There appears to be an internal wave between 100 and 150 m depth with increasing interface thickness and turbulent mixing occurring from left to right. The AMP measurements on profile 3227 (at right) show very high dissipation (of order 105 W/kg) from 100 to 140 m (Gregg, 1985, personal communication).

The upper ocean of the coastal regime is providing important advances toward understanding turbulent processes. For example, there is a linkage of mixed-layer and frontal dynamics over the shelf. The two are intimately coupled, and it seems clear that the simple, one-dimensional, mixed-layer models that work in the deep ocean will not generally be applicable over the shelf. Further, laboratory wave-tank experiments demonstrate that breaking surface waves can contribute to mixed-layer deepening. Again, it has been found that surface waves, often neglected in past studies, may play a substantial role in shelf processes. The study of turbulent processes in the coastal ocean is at a very exciting juncture. New processes are being recognized that will lead to a rapid revision of our understanding over the next several years.

Strait Dynamics

Understanding of the flow through straits has improved substantially in the last few years with the application of hydraulic models to the two-layer exchange between the Mediterranean and Atlantic basins through the Strait of Gibraltar. Low-salinity Atlantic water flows into the Mediterranean in the upper layers and a nearly equal outflow of high-salinity Mediterranean water exists from the Strait into the Atlantic in the deeper layers. Mass and salt conservation arguments relying on salinity observations in the Strait have

long provided the basis for understanding the exchange. A dynamical argument combined with an assumption of large mixing in the Mediterranean Sea yields a hydraulic control condition for two-layer flow at the sill, and allows one to predict the salinity excess of the Mediterranean water over the incoming Atlantic water, and hence, to predict the magnitude of the flows through the Strait. The Strait of Gibraltar is really a complicated series of sills and narrows so that the critical hydraulic control condition may occur in different parts of the Strait during different parts of the semidiurnal tidal cycle; the entire strait problem must be solved before the location of critical flow can be identified. The hydraulic control problem has been extended to show how seasonal changes in the water masses in the Strait can affect the locations of critical and supercritical flows. These models have served to establish the essential nonlinearity of strait flows and have emphasized the complexity and the necessity of solving the complete problem, including nonlinearity, time dependence, and realistic strait configuration.

Because of the theoretical difficulties in solving the complete problem, a year-long field program was carried out in the Strait of Gibraltar from October 1985 to October 1986 as part of the ONR ARI on Strategic Sea Straits. The purposes of this experiment were to measure the flows through the Strait of Gibraltar, including their temporal variability over tidal to seasonal time scales, and to assess the importance of nonlinearity, time dependence, friction, mixing, and rotational effects on the dynamics of the two-layer flow through the Strait. While the measurements are in early stages of analysis, preliminary results suggest that enormous turbulent dissipation and mixing events regularly occur near the sill during part of the tidal cycle (Figure 2-5); that hydraulically critical flow occurs at various locations in the Strait during different parts of the tidal and seasonal cycles; and that low-frequency fluctuations in the inflow and outflow are strongly correlated with winds and perhaps with atmospheric pressure. Analysis of this rich data set will surely lead to further advances in understanding the processes controlling the dynamics of flow through straits and in the ability to model such flows for future applications.

Upwelling Filaments

Another general area of advance in coastal physical oceanography has been in understanding the transition between deep ocean and coastal flow structures. Perhaps the most spectacular new findings involve offshore protruding filaments of cold water protruding seaward off California (see Figure 2-6). Discovery of these features revolutionizes current understanding of eastern boundary currents and coastal upwelling. Exploration of filaments has been made possible by concurrent advances in both satellite remote sensing and earthbound observational systems such as radio- and satellite-tracked drifters and the acoustic Doppler current profiler. The cold filaments seem to be characterized by energetic currents (Figure 2-6), sharp fronts, large offshore scales (200 km or more), and much shorter alongshore scales (typically 50 km). The filaments appear to provide a mechanism for transporting large quantities of freshly upwelled water great distances offshore. The physical and biological implications of this injection are important. While there have been a few tantalizing glimpses of the structure of these features, the dynamics of filaments are quite unknown.

Marginal Seas

Finally, marginal seas represent special parts of the coastal ocean that have not yet received extensive attention either experimentally or theoretically. Many marginal seas

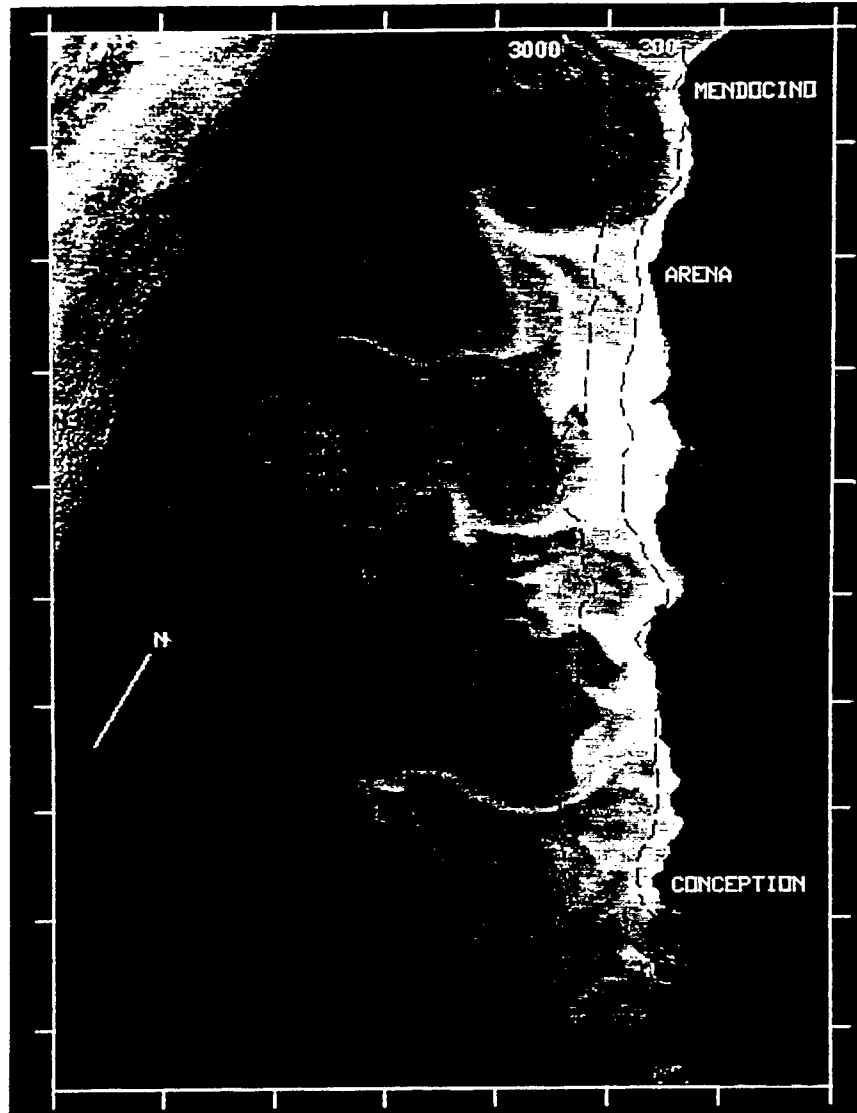


FIGURE 2-6 An infrared image of the California Current taken on 15 June 1981 at 0400 UT by the satellite NOAA-6. Light gray shades correspond to cold water; the range of temperatures is approximately from 11°C nearshore to 18°C offshore. The spacing of the grid is 100 km. Cold upwelled water is seen on the continental shelf and slope shown by the 300 m and 3000 m isobaths (dashed lines). Large meanders of the south-flowing California Current between Cape Mendocino ($124^{\circ}20'\text{W}$ $40^{\circ}20'\text{N}$) and Point Conception ($120^{\circ}30'\text{W}$ $34^{\circ}30'\text{N}$) are accompanied by several upwelling filaments extending up to 400 km offshore. (Adapted from Flament, Armi, and Washburn, 1985.)

like the Gulf of California and the Yellow Sea have anomalously high tides. Because of their correspondingly large tidal energy dissipations these seas have a substantial effect on the global tides as well. Within the sea, local tidal currents over the bottom generate turbulence that can, in certain cases, lead to tidally well-mixed regions, persistent primary and secondary circulations, and regions where new water masses are formed by blending of adjacent water masses.

Characteristics of the wind-driven response (both locally and nonlocally excited) in

marginal seas can vary markedly from the response in open coastal regions because the semi-enclosed topographic setting allows generation of significant along-axis pressure gradients analogous to those in lakes. The dynamics of marginal seas are expected to vary considerably with their topographic configuration and with the types of atmospheric momentum and buoyancy forcing to which they are exposed. To date, good exploratory studies of the East China and Yellow seas and the Gulf of California have been made, but there is a clear need to extend our conceptual understanding by investigating other marginal seas in different types of semi-enclosed basins.

NAVAL RELEVANCE

Naval warfare involves conflict on three scales—local (single country), regional (subcontinent), and global; geopolitical considerations virtually ensure that all scales will include operations within the coastal zone. Although this review focuses on coastal oceanography, it is well known that the marine atmospheric environment in the coastal zone has distinctive properties associated with the triple interface of sea, air, and land, and that such effects as anomalous radar ducts, low-level wind shear, and marine fog have strong impacts on air warfare, surface warfare, and communications.

Amphibious operations are still the primary means for the Navy and Marine Corps to transport power ashore. New air-cushion landing vehicles operate very effectively under most surf-zone conditions, but forces ashore must still be supplied by conventional transport methods, which are highly susceptible to adverse changes in the nearshore environment. Accurate nowcasts and forecasts of nearshore environmental parameters remain vital to the success of amphibious and unconventional operations (special warfare) that involve transiting the nearshore zone. This capability requires a thorough understanding of the fundamental processes of energy and momentum transfer through the nearshore zone.

Implicit in all coastal operations is the importance of mine warfare, including both mining and mine countermeasures. Mining is the most efficient means to attack naval forces in their home waters, strategic bases, and choke points. Recognizing the Soviet practice of dispensing their fleet into coastal basin areas and logistic support sites for protection during crises and wars, the U.S. Navy has given new attention to offensive coastal mining, in addition to the traditional emphasis on choke point mining. Conversely, mine countermeasures are notoriously difficult in the complex environments of coastal regions where mines must be cleared to permit amphibious operations or sorties of our forces from bases. The common scientific thread in these bottom-influenced domains is the need for a clear understanding of the small-scale shelf dynamics that underlie the environmental variability.

Most significant of all is the sharply increasing importance of coastal ASW in maritime strategy. Defensively, the presence of enemy cruise missile submarines in the coastal oceans around the United States is a particularly dangerous threat. Offensively, there is a strong and steadily rising emphasis on forward ASW. In both instances, acoustics is of prime significance. Here we call attention to the importance of acoustics in the deeper parts of the coastal ocean and to nonacoustic ASW over the entire coastal domain. (The problem of shallow water acoustics is well appreciated and is treated in the report of another National Research Council panel, *Research Opportunities in Underwater Acoustics* [National Research Council, 1986].) These considerations dictate expanded emphasis on such areas as coastal eddies and fronts, coastal ocean mixed-layer development, and small-scale turbulent fields. Further, they demand thorough understanding of the oceanographic and meteorological characteristics and dynamics of coastal zones that have been of little operational interest for

the last few decades. The gulfs of Mexico and California and fjords are examples of coastal regions and unique environments where nowcasting and forecasting capabilities must be available to support anticipated operations.

The panel also notes that Navy-relevant research topics traditionally studied only in the open ocean may be of no less importance to coastal operations. Wherever possible, oceanographic research should address modifications unique to coastal environments. Two immediate examples are the research programs focused on waves and bioluminescence. Renewed research initiatives on waves would be incomplete without a consideration of bottom and coastal interactions; and if bioluminescence is at all of concern for ASW, that concern is intensified in coastal areas, where traditional acoustic techniques perform poorly.

THE ONR COASTAL SCIENCES PROGRAM

The present ONR Coastal Sciences Program focuses largely on topics in coastal physical oceanography. Rather than distribute its limited resources on the study of a broad range of problems, it has instead concentrated attention on a few selected topics, all of which are of prime scientific importance and have some potential to address perceived naval needs. Under the core funding, the program now addresses Nearshore Processes and Coastal Oceanography.

Nearshore Processes

The Coastal Sciences Program (previously Geography Programs) has been involved in nearshore processes for more than two decades. Over the past few years, the focus has narrowed to studies of the fundamental hydrodynamic processes that govern the nearshore zone and beach evolution, with lesser emphasis on pure geomorphology. Present topics of interest include surf beat and edge waves, nearshore turbulence, nonlinear processes in shoaling waves, and sediment transports.

Coastal Oceanography

Under core funding, studies of larger scale processes of the coastal ocean were initiated in the early 1980s and now form the conceptual centerpiece of the program. Areas of interest have been dynamics of marginal seas (experiments in the East China Sea [1983-1984] and Gulf of California [1984-1985]), coastally trapped waves (Australian Coastal Experiment [1983-1984]), wind forcing of shelf circulation, and various theoretical and laboratory efforts. At present, this program component also provides major support to ARIs.

The following are descriptions of the coastal sciences ARIs.

Strategic Sea Straits

This ARI (FY 1981-1987) has been devoted to achieving an understanding of the principal dynamic processes that govern the central regime of sea straits, with emphasis on straits whose width is comparable to the Rossby internal deformation radius. These passages between major water bodies represent a major control on ocean circulation on a broad scale and have interesting and unique local dynamics as well.

Straits research was substantially revived by the ARI after several decades of comparatively little effort. The centerpiece of this area is the Gibraltar Experiment (1985-1986), which is now in the analysis phase. The Lombok Strait Experiment (1985-1986) provided

the first direct measurements of through-flow from the Pacific Ocean to the Indian Ocean. The first moored observations that penetrated the core of the Florida current were made in studies of the Florida Straits (1983-1984), and the first dedicated study of comparative straits geomorphology was undertaken in the straits of Jubail and Aqaba in the northern Red Sea (1982). The influence of straits on regional circulation was examined in the Alboran Sea Experiment (Donde, Virginia, 1986).

This ARI has stimulated significant research on the physical dynamics of straits. Experimental emphasis has been placed on building up a high-quality data base on transports, and on studying the remarkably intense mixing processes that can take place within the passages. Laboratory and analytical modeling efforts have focused on understanding the processes that control both the exchange through straits and the structure of the flow within them. Additional support must be found to fund the full analysis and synthesis of the excellent data base collected under this ARI, which is concluding with inadequate funds for the full analysis of the extensive data set collected.

Remote Sensing

The Remote Sensing ARI (FY 1981-1986) was an amalgam of efforts within the Physical Oceanography, Arctic, Mathematics, and Coastal Sciences programs. For its part, the Coastal Sciences Program focused attention almost exclusively on the physics of remote sensing by synthetic aperture radar (SAR) in part because the SEASAT SAR images had shown the local bottom topography in coastal waters, although SAR images of ship wakes mainly drive the naval relevance.

The cornerstone of the SAR effort was the Tower Ocean Wave and Radar Dependence (TOWARD) Experiment (1984-1986). Central to the science was an examination of the small-scale surface physics that governs the imaging process. The primary field site was the Naval Ocean Systems Center (NOSC) Tower near San Diego, roughly a mile offshore in about 20 m of water. The scientific goal was to determine the physical principles that must be known for the prediction of the capabilities and performance of SAR in sensing and measuring the ocean surface. Some investigations of internal waves were also conducted simultaneously. The fields of ocean hydrodynamics, radar backscatter, and SAR imaging processes were first researched separately and then combined. Experiments are still being evaluated under a new ARI (not funded through the Environmental Sciences Directorate) expressly dedicated to SAR only.

Under the new ARI (1986-1991) preparations are under way for follow-up experiments, including the more complicated, often nonlinear ocean dynamics revealed by the higher radar frequencies (C, X, Ku band), with a SAXON (SAR and X-band ocean nonlinearities) experiment now scheduled for late summer 1988 and spring 1989. This experiment will include acoustic sensors and special investigations concerning the microlayer on the ocean surface and its influence on radar backscatter and hydrodynamics.

Coastal Transition Zone

The largest component of the Coastal Sciences Program, the Coastal Transition Zone ARI (1986-1990) focuses on the origin, evolution, and dissipation of highly energetic coastal jets that penetrate laterally into the ocean interior for hundreds of kilometers (Figure 2-6). This program has been started to study mesoscale and smaller-scale processes occurring in the coastal transition zone (CTZ), off mid-latitude upwelling centers, where cold streamers of coastal waters extend far into the open ocean. The cold streamers, first seen during the

NSF-sponsored Coastal Ocean Dynamics Experiment (CODE), represent large, localized surface temperature anomalies, and are often accompanied by intense fronts and energetic jets. The initial objective of the program is to obtain a comprehensive, high-quality data set from the CTZ off northern California. An active modeling program is also included. Particular emphasis is being placed on issues of turbulent dissipation of the features, and on understanding their relation to the ambient oceanic eddies and other flow features in the California current system. These jets are known to have a dramatic influence on coastal biological communities. This ARI is jointly managed by the Coastal Sciences and Oceanic Biology programs. This effort is primarily experimental, with pilot and full experiments currently scheduled for the late spring and summer of 1987 and 1988.

PROMISING FUTURE RESEARCH

The long-term goal of coastal physical oceanography is to achieve a predictive capability for current, density, and bathymetric changes within the coastal ocean. The subdiscipline is currently in a position where this capability is in view, however distantly. Predictability will require considerable advances in some areas, but we can now see what those advances must be. Coastal oceanography is an experimental science, and the need for continued field and laboratory experimental programs, both small and large, must be clearly recognized and emphasized. Recent advances in all aspects of coastal oceanography have been made possible by major field experiments utilizing state-of-the-art instrumentation developed for separate upper-ocean or deep-water experiments, and explicitly for these coastal studies. The synergism between coastal and upper-ocean, process-oriented studies should be recognized and encouraged. (This collaboration should be particularly important in new ONR studies of surface mixed-layer dynamics, surface gravity wave generation, dissipation and mixing through wave breaking, and bioluminescence.)

Some particularly promising and important areas for emphasis in coastal sciences in the next few years are described in the following sections.

Nearshore Processes

Good progress is being made in understanding waves and alongshore currents on topographically simple beaches. Comparable advances have not been made, however, in understanding cross-shore mean flows. These flows are generally shoreward near the sea surface and offshore near the seabed (undertow). Undertow may play a critical role in beach erosion by moving sand offshore during storms. Despite its clear importance to beach stability, little is known about undertow other than that it is generally weaker than alongshore flows, may have direction reversals across the vertical water column, and can be strongly intensified by both irregular beach bathymetry and nonlinear flow instabilities. Very careful field work will be needed to measure accurately the cross-shore mean velocities in the presence of the more energetic oscillatory cross-shore and steady alongshore flow components. This subject area clearly is ripe for both observations and modeling.

The surf zone demonstrably is a region with high levels of turbulence. Surprisingly, little more can be said regarding small-scale motions in the nearshore. There are, for example, no field measurements that study the vertical distribution, temporal and spatial scales, or any other aspect of surf-zone turbulence. It has been hypothesized that turbulent Reynolds stresses are central in determining the vertical structure of undertow and suspended sediment, but these speculations remain totally untested. An experimental research effort in

nearshore turbulence and small-scale motions (boils, roils, rollers) seems bound to provide new and useful insights, since virtually nothing is known at present.

Another area in need of advancement is the coupling mechanism between the flow field and sand transport. Some rather limited progress has been made on the small-scale dynamics of sand suspension and transport in the surf zone, but a need exists to pursue these studies and to develop instrumentation to measure sand transport very near the seabed (bedload). Both bedload and suspended sediment results then need to be extended to the macroscale, yielding bulk parameterizations of transport. Following this extension, the next step would be to formulate a major field program that encompasses the generation of both alongshore and across-shore currents by swell, the transport of sediment by nearshore currents, and the effect of the changing topographic configurations on the flow field. Conceptually, the flow-sediment problem can be thought of as a two-layer fluid that derives its energy from the incoming wave field. Using this analogy, the new problem is to understand and quantify the coupling between layers on a macroscopic scale.

Existing experimental tools for measuring currents in the nearshore are limited to electromagnetic and acoustic travel-time sensors, which measure velocity in a small volume. Although these sensors were developed in the 1970s, they have never been upgraded or extensively calibrated. The performance of these sensors in highly turbulent flows with significant steady and oscillatory components is not well known. Careful laboratory experiments could refine understanding of these traditional sensors. Additionally, and perhaps more important, recently developed instrumentation such as acoustic Doppler current meters and trackable Lagrangian drifters need to be adapted to the nearshore environment. These sensors could lead to revolutionary advances in mapping rip currents and other features of the nearshore circulation. The response of drifters to waves will be especially important in the surf zone.

Instruments for measuring sediment concentrations and fluxes are relatively new. Acoustic and optical backscatter sensors have yielded very promising results, but further refinement of these sensors has virtually ceased in the United States. A vigorous program of instrument development for nearshore applications should be very fruitful. A stable and significant funding commitment would be necessary, however, to motivate the long-term effort typically involved in such development work.

Intermediate-Scale Shelf Dynamics

Recent wave-like models of shelf circulation have proved remarkably successful in their ability to rationalize measurements, such as those made during ACE and CODE, of regional-scale pressure and alongshore current fluctuations over the continental shelf. Knowledge of temperature, density, and across-shelf velocity variations has not kept pace. For example, programs such as OPUS and CODE led to the current CTZ study of upwelling filaments. Those features that exist offshore from the shelf represent substantial current and density variability. Even over the continental shelf, current understanding of short alongshore variability is quite weak.

The wave-like theories are inadequate over the continental shelf because of their failure to include variability on alongshore scales of 1 to 50 km, which have been shown to be crucial for the determination of thermal and across-shelf current variability. This weakness must be addressed because of the importance of understanding hydrographic variability (particularly fronts) in range-dependent acoustics. The study of such small-scale phenomena will require an entirely new modeling approach and careful attention to small-scale variations in topography and in the wind stress forcing. The small-scale dynamics are less likely to

be linear than the large-scale dynamics, and hydrodynamic instability may well play a dominant role. Further, because of the small scales involved, it is probable that much of the interesting dynamics will be highly baroclinic (dependent on vertical stratification).

While the study of motions on horizontal scales of 1 to 50 km is almost certainly crucial to our overall understanding of shelf processes, the method of exactly how to proceed is as yet uncertain. A rigorous modeling program, though, would be a useful starting point. Effects of instabilities and of the ubiquitous small-scale structures in wind and topography could be studied with laboratory or numerical simulations. After these results are compared with existing field observations, a more definite plan of attack can be formulated.

Turbulent Processes

While it has long been known that most of the dissipation of the ocean surface tides occurs in shallow water, the full importance of turbulent processes in the coastal ocean is only now being recognized. For example, the large dissipation in straits associated with internal tides has global and strong local implications. It is important to pursue this line of study in settings as simple as possible to allow a firm physical understanding and accurate parameterization. Laboratory and other forms of modeling should also continue apace on this subject. Internal tides generated at the shelf break and other abrupt topographic features can also cause strong turbulent mixing on both the shelf and slope.

Work on bottom boundary layer processes should also proceed, particularly to make more realistic models that incorporate spectrally broad wave fields and give bottom stress results averaged over horizontal scales that are useful in circulation models. Further, there is a need to understand the pressure drag associated with bottom roughness with heights comparable to the velocity boundary layer thickness. These effects are important to the long-term goal of predictability because no shelf or marginal sea circulation model can be accurate without a good parameterization of bottom drag, which enters the dynamical balances at the lowest order.

Finally, surface mixed-layer physics and the intimately related issue of coastal fronts are research areas ripe for increased emphasis. A modest body of theory has been developed that puts forward ideas to be tested with observations. Theory, in turn, is limited by our meager knowledge of the detailed turbulent processes occurring in the surface layer and near fronts. A major field program or programs on both the surface mixed layer and coastal fronts thus is very timely and should lead to advances in both our dynamical and predictive understanding of these features. Fortunately, for all of the problems involving turbulence in the coastal ocean, appropriate observational capabilities are now largely in hand.

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3

Marine Geology and Geophysics

Marine geology and geophysics (MG&G) are subdisciplines of oceanography studying the composition, redistribution, and derivation of the solid and particulate matter near, on, and below the ocean floor.

HISTORICAL DEVELOPMENT

During World War II a strong, mutually beneficial interaction developed between the Navy and the marine geology and geophysics community. This relationship, which continues today, developed naturally from the Navy's requirements for environmental data to support the conduct of amphibious operations, the laying and clearing of mine fields, and the construction of new port facilities. The extensive survey data base acquired in support of military operations, using bathymetric, navigational, and bottom-sampling tools developed by the Navy, led to the acceptance of plate tectonics and developed new hypotheses for the creation and vertical motion of oceanic islands.

In the years after the war, researchers supported by the Navy, using surplus ships, explosives, and echo-sounding equipment, mapped the fracture zones that dominate the bathymetry of the eastern Pacific and established the uniformity and thickness of the ocean crust. Technological advances in sonar led to the development of seismic reflection profiling equipment and bottom-penetrating echo sounders. These hardware improvements allowed researchers to study the subbottom structure of the ocean basins and develop new concepts of how they evolved. Ultimately, these efforts contributed to the development of the unifying concept of plate tectonics. Varied Navy interests, including placement and search and recovery of valuable equipment on the seafloor, accurate navigation, and environmental support for magnetic detection of submarines, were principal drivers in the development of sophisticated new instrumentation such as the multibeam bathymetric mapping system and the DEEPTOW bottom-survey package. This technology base supported extensive marine geological and geophysical exploration for petroleum; in return, towed hydrophone developments within the geophysical exploration community are now seeing service with submarines and ships.

The overlap between the needs of the Navy and the academic marine geology and geophysics community is substantial in the light of major new efforts in ASW toward lower

frequency acoustics, the distributed field of sensor arrays and renewed interest in marginal seas and coastal zones. This overlap is especially noteworthy in five areas.

The Navy has traditional concerns with issues such as bottom scattering, absorption, and reverberation. These concerns imply substantial interest in subbottom acoustic propagation and its variation as a function of frequency, especially at low acoustic frequencies. These low frequencies are also of great interest to academia, as analysis of these data provide the academic geoscientists with the structure and composition of the crust and upper mantle under the oceans.

Operational ASW interests and associated MG&G research have properly emphasized the deep oceans. Especially important has been understanding the basic morphology of the sea floor that is created at the ridge crests. However, there is now a strong Navy interest in the study of margin limited environments. The known difficulties of traditional shallow water acoustics imply a need for innovative research on the shelf to vastly improve understanding of the transmission of acoustic and elastic waves in shallow water. These regions are also of great interest to geoscientists, where the most modern techniques are being used to investigate the basic structure and to test models of continental basin and margin formation.

The Navy has an increasing need to understand the differences in performance of different sensor types. The requirement is to move away from descriptive treatments toward the ability to model low-frequency (0.1 to 400 Hz) signal and noise for on- and sub-bottom sensors. This approach is very similar to the requirement of the marine geology and geophysics community where quantitative treatments are required of the likely signal to noise ratio and the coupling parameters of the new deep sea instruments that will be the mainstay of future academic research in low frequency acoustics on the seabed.

The Navy has a major continuing interest in sedimentary processes and an interest in bottom dynamics and ocean engineering. There is increasing concern with bottom stability on the shelves and deep ocean. This area is also of great interest to the academic community, where the HEBBLE project has revealed the dynamic nature of sedimentary processes on the seabed and their importance to shelf/slope stability.

Coupled with an interest in understanding the propagation of acoustic waves, the Navy is also interested in the bottom terrain itself. Again, this interest applies to continental margins and the deep oceans. Like the Navy, the academic community is interested in quantitative characteristics of physical, magnetic, geochemical, and electrical processes involved in constructing this terrain and in using this understanding to elucidate the fundamental processes by which the floor of the oceans and their margins are created. The high latitudes are difficult places in which to carry out marine geology and geophysics research and hence have been less studied than the rest of the oceans. The Navy has a specific interest in better understanding of the Arctic. This is another area of natural overlap between good science and Navy relevance.

UNIFYING CONCEPT

Plate tectonics forms the basic framework for MG&G at their largest scales. In this concept, the surface of the earth is envisioned as a set of internally rigid, interlocking plates including both continents and ocean floor (Figure 3-1). The plates are in constant motion. Earthquakes define the plate boundaries, marking regions where plates form, destroy, and move past each other. Plate creation forms the oceanic crust, and plate destruction creates island arcs and continents. The sediments result from the deposition of particulate matter onto the ocean crust. Both the crust and the sediment move with the plate to which they are

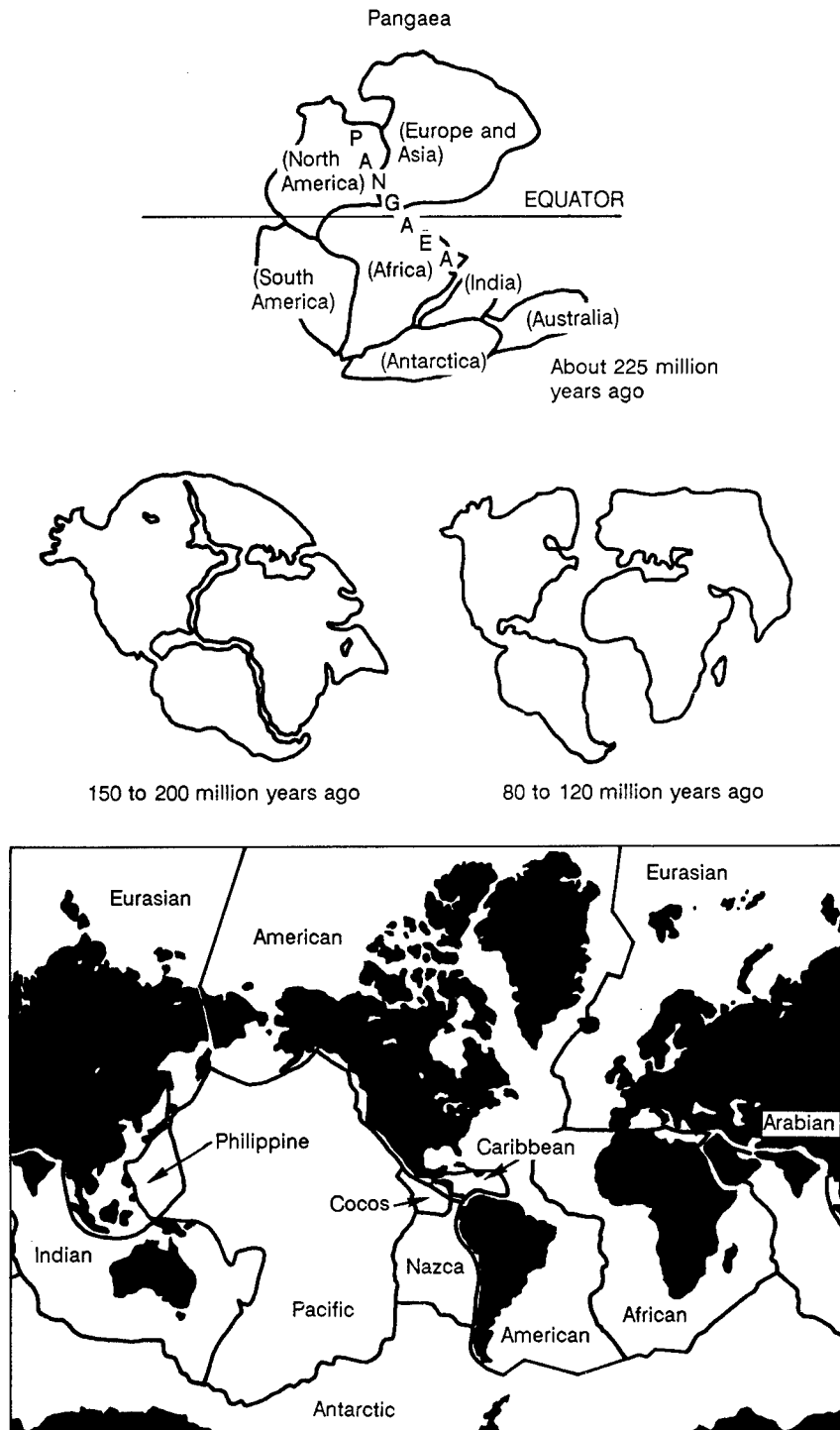


FIGURE 3-1 The changing position of the continents according to the concept of seafloor spreading (Ross, 1982).

attached. The 50- to 100-km-thick plates lie on top of a convecting upper mantle. The plate and the portion of the upper mantle moving with the plate are known as the lithosphere.

TRENDS AND PROGRESS

The past 30 years were ones of great success for this MG&G. Observations of the morphology, magnetic signature, gravity field, structure, and composition of the ocean floor collected on MG&G expeditions provided the basic data for the development of the theory of plate tectonics. The ONR provided much of the funding for the rapid development, testing, and acceptance of this fundamental concept.

The plate tectonics concept worked so well as a description of the ocean floor that little more was required than to select key areas and make the appropriate observations. Almost all the critical simplifications appear to be understood, and the value of the concept in providing new insights from additional data of the same kind appears to be exhausted. As a consequence, the research strategy in MG&G has changed from a purely descriptive approach to one that attempts to understand the basic processes that have created the ocean crust and lithosphere and deposited sediment in the deep-sea basins. New and improved instrumentation has rapidly accelerated this change.

This discussion of trends and progress is hierarchical, based on scales of distance and time. In addition, the processes are separated into two categories; those involved in understanding crust and mantle and those involving the sedimentary record and the particulate matter. When discussing the processes that create and modify the ocean crust, the ocean lithosphere, and the upper mantle, the following scales are considered:

- global processes: whole-earth geodynamics,
- mesoscale processes: crustal genesis and evolution, geophysical and geochemical models, and
- fine-scale processes: hydrothermal venting.

The discussion of sedimentation in the deep sea is divided as follows:

- the sedimentary record: role of the ocean through time, and
- microscale processes: sediment dynamics and the benthic boundary layer spanning the shorter mesoscale and small scale of the physical oceanographer in both space and time.

Global Geodynamics

Following the great success of seafloor spreading and plate tectonics, attention has turned to understanding the large-scale motions of the earth. In particular, earth scientists have focused on the creation, destruction, and modification of the oceanic lithosphere and the way in which the continental lithosphere deforms as it breaks up before and during the initial formation of ocean floor.

Intrusion of molten material at a spreading center and the consequent loss of heat of this material creates the oceanic lithosphere. A particularly fruitful approach to understanding this process has been to model the oceanic lithosphere as a thermal boundary layer on top of a convecting upper mantle (Figure 3-2). Within this large-scale (100 to 1000 km) approximation of this complex system, earth scientists have concentrated on computer modeling of melt segregation and transfer to understand the intrusion process. In addition, investigations of homologous processes such as the convection, intrusion, and cooling of molten wax and similar processes on lava lakes, such as that at Kiluea in Hawaii, are most useful. In the future, a combination of the computer modeling and dynamically scaled fluid-solid models will provide a quantitative way in which to parameterize the physical processes involved in the creation of these boundary layers.

Downward movement into the upper mantle by one plate under another (subduction) destroys the oceanic lithosphere. The shallow earthquakes that occur in the downgoing

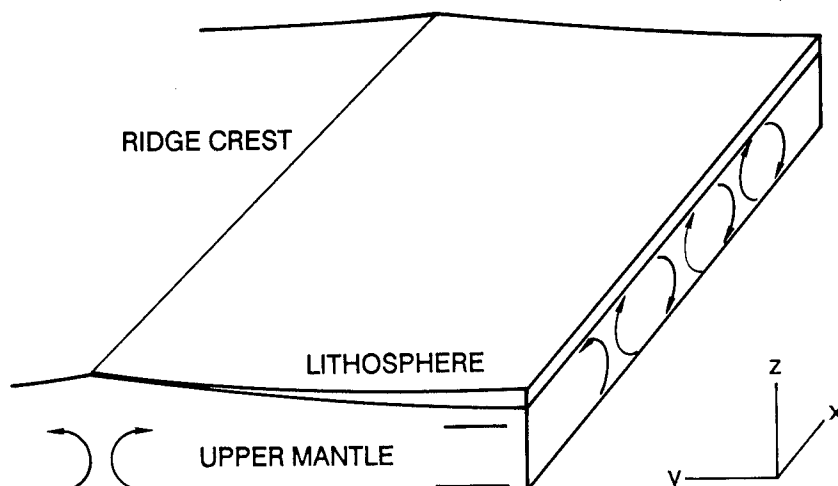


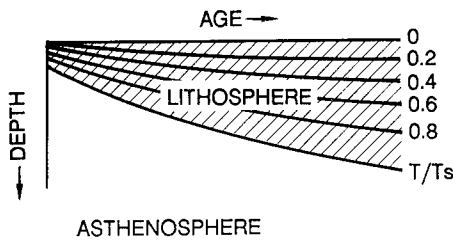
FIGURE 3-2 Sketch of two-scale convection in the upper mantle underlying oceanic lithosphere. The two-dimensional section A-A' is parallel to the spreading ridge crest and extends to a depth of about 700 km. The arrows show the sense of motion of a possible flow field restricted to the upper mantle.

slab define the width and type of deformation in the active zone. The collision of the two plates creates a structurally complex region as sediment is scraped off the downgoing plate and stacked up against the massive igneous volcanism of the island arcs on the overlying plate. These areas of active subduction evolve into inactive accretionary zones such as the Franciscan along the coast of northern California. Studies of these areas of active subduction provide fundamental information on the formation of new continental material. Data being gathered by multichannel seismic (MCS) techniques provide much important information on the style of deformation occurring at these active plate margins. It now appears that sedimentation is eroded from some styles of plate margins while accumulation occurs on others. Drilling has yielded additional information on the structure and fluid pressure in the toes of the accretionary prisms formed by the accumulating sediment. Experimental and theoretical investigations of the behavior of wedges of analogous materials such as sand and ice provide further valuable information.

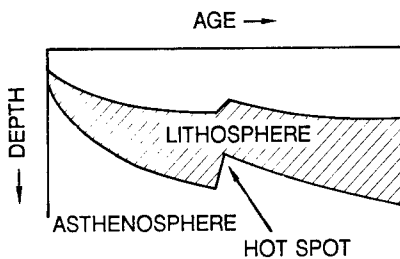
Modeling the oceanic lithosphere as a cooling boundary layer on top of a viscous convecting upper mantle accounts for the observed increase in depth of the ocean floor with increasing age. On the oldest ocean floor this depth approaches an almost constant value and presents evidence that the thermal boundary layer approaches equilibrium conditions. Bathymetric and gravity studies over seamounts have shown that the upper portion of the cooling boundary layer can be modeled as an elastic plate whose thickness increases with age. The fluid dynamic approach has been of limited value in the past, but it presents a great opportunity to examine both the oceanic lithosphere and the upper mantle beneath it as one geodynamic system. For example, can we tackle the question of the exact physical nature of the lithosphere and design experiments to distinguish between thermo-mechanical and simple thermal boundary layers (Figure 3-3). Determining the driving forces of plate tectonics remains an important and difficult problem. Are they dominated by the excess mass of the downgoing slab or are lithospheric drag forces important? What is the role of ridge push versus gravitational sliding forces? There is evidence that the Hawaiian swell results from the interaction of a thermal plume in the upper mantle with the oceanic lithosphere. Can we now investigate whether the other seamount chains such as the Line Islands or aseismic ridges such as the Ninetyeast ridge were created by a similar

a. SIMPLE COOLING ' \sqrt{t} '

(1) TEMPERATURE STRUCTURE

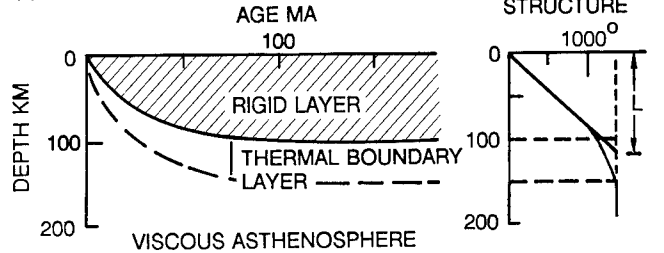


(2) INFERRED INTERACTION WITH HOT SPOT



b. THERMO-MECHANICAL 'PLATE'

(1) DEVELOPMENT OF OCEANIC PLATE



(2) INFERRED INTERACTION WITH UPPER MANTLE PLUME

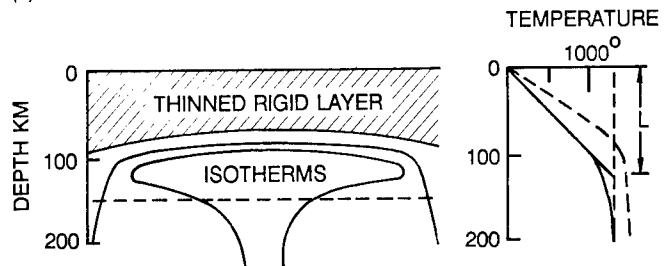


FIGURE 3-3 Boundary layer models of oceanic lithosphere. Two different possible models for the temperature and inferred interaction with a mantle hot spot of the oceanic lithosphere: (a) the simple cooling model (Crough, 1978) and (b) the thermo-mechanical plate model (Parsons and McKenzie, 1977). The simple cooling model assumes a rigid plate, while convection and mixing are part of the thermo-mechanical model.

mechanism? These hotspot traces appear to form a stable reference over long geological periods, showing absolute plate motions. The geological and geophysical properties of these enigmatic features are exciting targets for ongoing research.

Analysis of the long-wavelength geoid anomalies over these swells and the discovery of geochemical anomalies on them will go a long way toward determining whether there is a relation between geochemical and thermal variations in the upper mantle. Other observations that will play an important part in elucidating the structure of the upper mantle beneath the plate are seismic tomographic measurements of the three-dimensional elastic velocity structure within the earth, heat flow measurements investigating the thermal anomalies associated with mantle swells, and electrical measurements that indirectly constrain temperature and melt differences in the upper mantle beneath the oceanic lithosphere.

A problem of particular importance for understanding the global earth geodynamic system is the variation in thickness with age and position of the oceanic plate and how these variations relate to the convecting system below. Studies of the nature of the seismic signals from earthquakes have shown extensive wave trains associated with long-range propagation of oceanic Pn, Sn, and T phases. Useful hypotheses now exist for the excitation and propagation of these wave trains. Measurements of the behavior of these phases as a function of distance have revealed significant elastic velocity and attenuation contrasts at depths as great as 200 km under the northwest Pacific. The discrepancy between the very thick lithosphere implied by these measurements and the significantly thinner value

implied by previous flexure, thermal, and surface wave studies is attributed to differences in the parameters being measured. However, the observations taken as a whole, do not yet have a physically consistent explanation. The academic community has deployed seafloor instrumentation capable of operating at extremely low frequencies and has studied the interaction of long-wavelength, surface gravity waves with the underlying elastic lithosphere. Such instrumentation, capable of operating over wide bandwidths for periods of several years, will provide some of the basic data necessary to develop an integrated understanding of the dynamics of convection in the upper mantle and the relation of this convection to deformation in the lithosphere.

The continental lithosphere and crust deform both before and during the initial formation of an ocean basin. Extensional forces associated with this deformation thin both the crust and the lithosphere. This tectonic thinning provides the potential subsidence, through cooling, necessary for large accumulations of sediment on passive continental margins. The oil industry has extensively studied the shallow (<6 km) sediment fill on such passive margins, but they have not studied in detail the structure at greater depths. Academic scientists have used the conventional MCS techniques developed by the oil industry to investigate deep structures. In particular, the British Institutes Reflection Profiling System (BIRPS) group has been able to profile the crustal thickness on these margins and, in addition, have discovered major planar dipping reflectors both in the crust and at depths between 40 and 70 km within the mantle (Figures 3-4A and B). Major disagreements have surfaced in the interpretation of these results by industry and academic scientists. For example, the crustal thinning and subsequent subsidence in basement on the same MCS lines. Further, the deep faulting beneath the crust on the continents appears to have been reactivated at different times in the past. It implies brittle deformation at significant depth. These results are not compatible with laboratory studies on the rocks that are thought to lie at this depth. Due to the recent slump in oil prices, industry has donated to the U.S. academic community seismic systems that are close to the state-of-the-art. A major new initiative to understand the seismic structure of incipient, developing, and mature continental margins in both passive and active areas now appears financially realistic.

Marine geologists and geophysicists have applied the concept of plate tectonics with great success in determining the age and gross structure of almost all the ocean floor. However, problem areas remain, including the nature of the ocean floor and shelves surrounding the Antarctic continent; the structure of the lithosphere underlying the deep ocean basin; the origin of shallow aseismic ridges and oceanic plateaus; the internal structure of very slow-spreading, active ridge-axes; and the nature of the continental shelf of the Arctic. Currently, the Division of Polar Programs at the National Science Foundation (NSF) supports active marine geological and geophysical research in the Antarctic, but little or no organized research is being carried out in the Arctic.

Crustal Genesis and Evolution

The seismically active mid-ocean ridges that encircle the globe mark the spreading centers where oceanic plates are created. Intrusion of molten material at these spreading centers creates the surface or crustal layer of the oceanic plate. These ridges are largely passive tectonic features that result from lithospheric extension, and melt is produced by extensive "pressure release" heating in the uppermost mantle. The most volatile components of upper mantle material migrate to the surface to form the light, 5- to 7-km-thick oceanic crust. The general term "ridge axis process" is used to cover the 1- to 10-km scale processes involved in crustal generation and evolution.

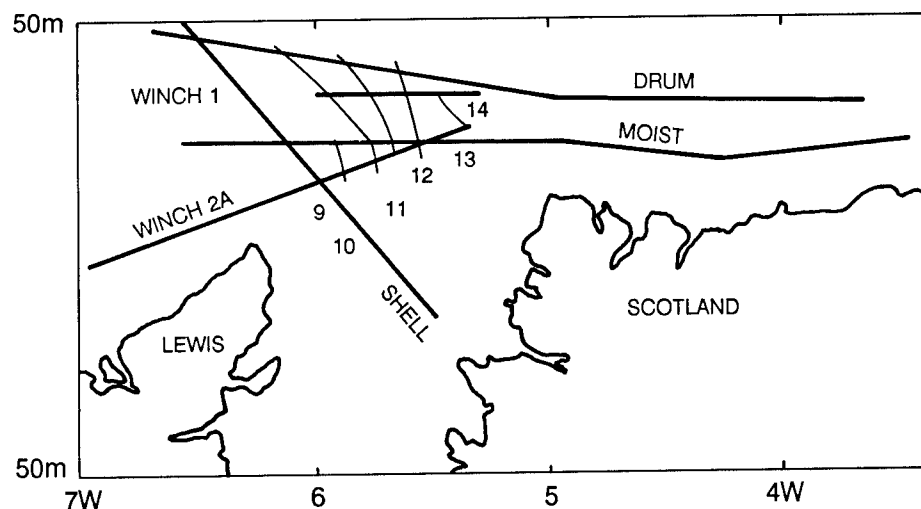


FIGURE 3-4A Location of DRUM 30-s profile shown in Figure 3-4B. BIRPS deep seismic profiles, MOIST, WINCH 1, and WINCH 2A are shown with a 15-s profile collected by Shell Expro UK Ltd. The depth in seconds (two-way travel time) to the Flannan Thrust is contoured to 14 s to show the three-dimensional structure.

Almost all of the ongoing tectonic and intrusive processes that determine the shape and structure of the ocean crust in the deep ocean basins take place at the ridge axis. As these ridges are shallow and covered by little sediment, they are relatively easily studied. The combination of the fundamental nature of the processes active at the ridge axis and the ease of observation provides the principal motivation for studying them. Nevertheless, interpreting these detailed investigations within the plate tectonic framework enables the prediction of the local variability of the ocean on scales of 1 to 10 km throughout the entire ocean basin.

For ease of presentation, the discussion of crustal genesis and evolution is divided into two sections: geophysical models and geochemical models. This separation is artificial but is necessary at the current stage of understanding of these processes since the geophysical observations imply continuity, whereas the geochemical data appear compatible only with a more discontinuous process.

Geophysical Models

Construction of geophysical models involves understanding the detailed structure and tectonics of the axis of the mid-ocean ridges, the physics of the intrusion process, and the overall topography of the median valley and the relation between transform faults (places where plates slide past each other) and the long, linear fracture zones observed in the deep ocean basins.

In the initial stages of understanding the structure of the ocean floor, emphasis was placed on widely spaced magnetic, gravity, and bathymetric profiles to determine how well the concepts of seafloor spreading predicted the overall tectonic pattern. More recently, the academic community has concentrated on observing in much greater detail the tectonic and magnetic fabric of the ocean floor. Recent discoveries (using the SEABEAM and SEAMARC systems partly funded by the ONR) such as overlapping spreading centers (Figure 3-5) and small nonoverlapping spreading centers fit easily within the concept of

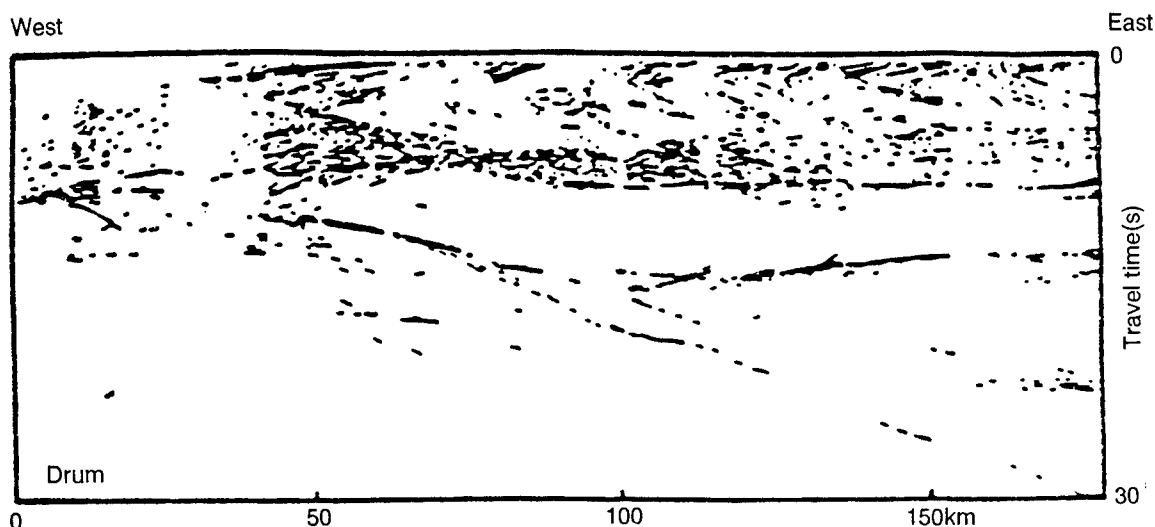


FIGURE 3-4B Line drawing of DRUM profile (location in Figure 3-4A) based on a preliminary stack of the data. The section is in seconds (two ways) and is true scale at a velocity of 5 km s^{-1} . The rotated half-grabens of the upper crust and the reflective lower crust and Moho are shown as well as the Outer Isles Fault (the Outer Isles Thrust of previous BIRPS papers). Within the mantle are seen three major features: the east-dipping Flannan Thrust; a subhorizontal reflector at 13-15 s between 80 and 180 km; and the 15-km-wide zone of horizontal reflections at 23 s at the eastern end of the section.

plate tectonics. Currently productive research on the tectonics of the ridge axis also involves the use of SEABEAM data and information from other deeply towed, higher-resolution instruments to investigate the spatial distribution of surface faulting and block tilting due to active extension at the spreading centers. These measurements, and similar ones using the broader-beam SEAMARK systems currently in use or being built by the academic community should help answer the major question of the relative contributions of surface extension and volcanic emplacement during seafloor creation. Remote sensing and field experience are now available to address the fundamental questions.

The size and distribution of the zone of partial melting that generates magma is an important and wholly unsolved problem (Figure 3-6). Multichannel and ocean bottom seismograph investigations have verified longitudinal continuity of the low-velocity zone where the magma that generates the crust resides. These observations may provide critical information for rationalizing the discontinuous processes necessary to explain the geochemical data and the strong geophysical evidence for continuity. Early electrical experiments have surprisingly demonstrated that the uppermost mantle is evolving in a lithosphere of low conductivity. The resistivity values imply water contents lower than those required by most models of crustal genesis. Currently, the size and magnitude of the magma chamber under the ridge axis, and whether it exists at all as a continuous feature constitutes a major unresolved problem (Figure 3-6).

Two other unknowns at this scale are the causes of the distinctive median valley on slow-spreading ridges and the influence of transform faults and smaller offsets on accretion at spreading centers. For the first, the current explanation of the median valley is the presence or absence of a strong lithosphere. The depth of the hydrothermal circulation probably controls the temperature and thus the strength of the lithosphere. Experiments to determine the depth of this circulation are needed. Mapping the influence of fracture zones and other axial discontinuities has shown that, away from these features, the ocean

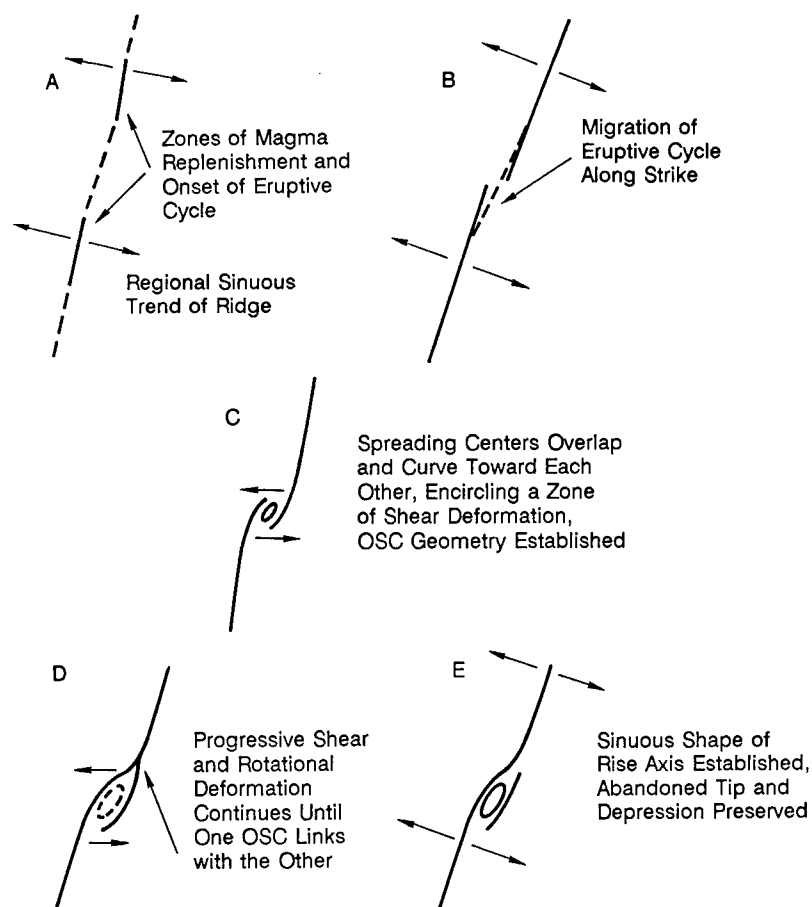


FIGURE 3-5 Evolution of oceanic spreading centers (OSCs) based on laboratory wax models (Macdonald et al., 1984).

floor has a remarkably uniform structure. For example, the thickness of the crust generated at the East Pacific Rise is indistinguishable from that of the mid-Atlantic Ridge, although the spreading rates differ by more than a factor of two. At the large scale (10 to 100 km), considerable order exists in the processes controlling the generation and evolution of the oceanic crust and lithosphere. Understanding these processes by interpreting carefully chosen field data within the framework of plate tectonics will provide the basis for providing basin-wide models of the tectonic, morphological, and velocity structure of the ocean crust and lithosphere.

Geochemical Models

Oceanic crust is formed by the extrusion of hot molten material onto the ocean floor. The lithosphere is created by the annealing of this material with the residue left behind in the uppermost mantle. The fundamental problem of geochemistry is to understand the formation and composition of this crust and lithosphere. These studies emphasize four specific processes: how the initial melt forms, segregates, and is transported within the mantle; how this melt differentiates on crystallization in a magma chamber; how the

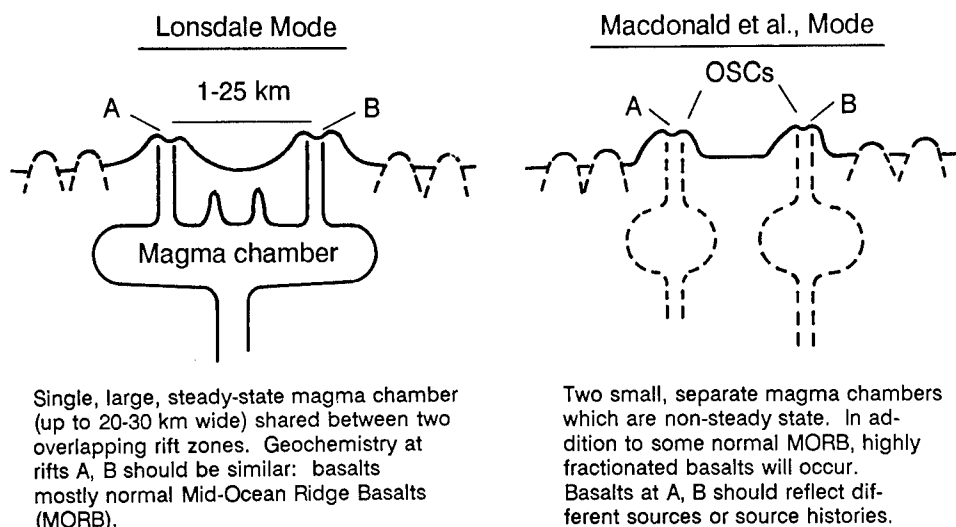


FIGURE 3-6 Two different hypotheses of the development of oceanic spreading centers: schematic cross-sections illustrate the geochemical implications of large versus small magma chambers (Lonsdale, 1986, and Macdonald et al., 1984).

differentiated material erupts at the surface; and what happens to the residue that is left behind.

Recent documentation of the morphology of the ridge crest and the distribution of rock types indicates that the intrusions occur three-dimensionally. The melt does not flow uniformly out of the mantle; rather, the flow is localized into a string of individual volcanic centers along the crest of the ridge (Figure 3-7). This new conceptual framework for sea floor crustal stratigraphy requires a careful examination of the chemistry of the rocks, with particular emphasis on their spatial variability. In addition, the convective instabilities must be verified analytically.

A particular interest involves understanding the chemistry of the residual mantle peridotites, which are abundant at fracture zones and between individual volcanic centers. To date, three independent research groups have shown that abyssal residual peridotites represent the depleted fraction of the mantle at the end of mantle upwelling and generation of ridge basalts. The same groups have also shown that their composition can be directly related to the basalt in the vicinity where they were dredged. This correlation has unequivocally demonstrated that a high degree of mantle melting is needed to generate ridge basalts and that it must occur in the vicinity of a mantle plume. This is the first direct confirmation of the localized plume hypothesis. This concept predicts that the crust should be thicker near a plume, which may indeed be the case. In addition, the dredging of large quantities of depleted peridotite at fracture zones and the absence of gabbroic rocks appears to demonstrate that Layer 3 (a historical term referring to a layer with seismic velocities of 6.7 to 7.0 km s⁻¹) is often absent in these regions. This finding confirms the thinning of the ocean crust near some fracture zones and its thickening elsewhere.

Current major problems in understanding the chemical composition of the oceanic crust exist on two scales. On the scale of 1 to 10 km, the major problem is to describe and understand an individual volcanic center over a time span of 0 to 20 million years. The essential question is: How does the mantle and segregated melt beneath the volcanic center change with time? Is the chemistry of the volcanic centers totally discontinuous, with each center sitting over its own instability point, or are the intrusions created from one large

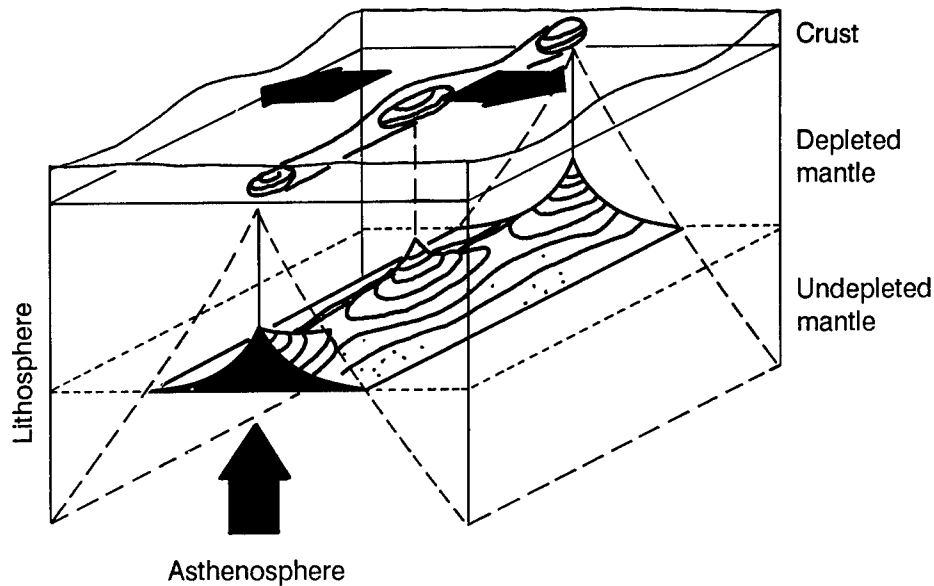


FIGURE 3-7 Possible model for buoyant upwelling of magma from a mantle melt-accumulation zone. Above a certain level (dotted lines), the rising asthenosphere passes through a zone in which partial melt can form and collects in a layer below the lithosphere and depleted mantle layer. Due to its lower viscosity and density, the partial-melt zone develops a gravitational instability that leads to regularly spaced concentrations of melt that rise to the surface to form crustal magma chambers (Whitehead et al., 1984).

magma chamber or from a suite of slightly less large magma chambers? On the larger scale the problems are two. First, how does the chemistry of the ridge crest rocks relate to the overall geodynamic system? For example, what is the relative importance of (1) distance from a mantle hot spot, (2) the spreading rate or, (3) the absolute motion of the spreading center in the mantle frame? Second, how is the chemistry of ocean ridge basalts affected by lateral heterogeneity on the largest scale? For example, what is the explanation for the anomalous isotopic concentration in basalts from the Southern Hemisphere?

The structure and composition of the oceanic crust will not be resolved until systematic sampling is carried out in situ. The currently popular view of the formation of oceanic crust from a string of volcanos formed over individual instability points must be thoroughly tested. Although the oceanic crust should be thinner away from the instability joints, no seismic evidence exists to firmly support his idea except at Atlantic fracture tower. It is interesting to note that it is at this fracture zone alone that unaltered mantle peridotites from beneath the crust are exposed. This more complex model differs a great deal from both the prior concept of a layered crust and from the model based on geophysical data. If we can verify the model at the ridge axis and understand the relation between compositional and structural variations and surface morphology, however, then it should be possible to predict the composition and structure of the crust in the rest of the ocean basins.

Hydrothermal Venting

On the scale of 1 to 10 km or less, the crest of the mid-ocean ridges consists of a string of volcanos. These volcanos interact with seawater during the intrusion process, thereby creating the spectacular hydrothermal systems observed at the ridge crest. The faulting involved in the rapid cooling of intruded magma and extensional forces active at the ridge

axis may permit penetration of seawater as deep as 5 to 10 km. This penetration affects both the cooling and the degree of alteration of the intruded rock. Thus, to understand properly the oceanic crust, it is necessary to examine the high-frequency, small-scale (<1 km) geometry of the hydrothermal vents under the three different settings in which they are observed.

In their most spectacular setting, at the crest of mid-ocean ridges, hydrothermal vents give rise to 350°C springs of sulfide-bearing water (the black smokers), which precipitate iron, copper, and zinc sulfides in chimneys and mounds. This type of hydrothermal system transports 3 to 5 percent of the heat flux of the earth to the surface and is responsible for a significant contribution to the flux of magnesium and other elements into or out of the oceans.

Deposition of sediment and the burial of the ridge crest create a second setting for these systems. In the Gulf of California, for example, lava is not extruded onto the seafloor but intruded into the sediment as sills, and the active spreading center is covered by 100 to 500 m of sediment. In this case, the permeability of the system is modified both by the presence of sills and by the relative impermeability of the sediments, and the chemistry is strongly influenced by reactions between hydrothermal fluids and sediment.

A third, recently discovered setting is the low temperature system in which the water emerges at only 10° to 20°C. It does not appear to be hot water that has been entrained and diluted by cold seawater in the subsurface, but rather simply a system that, as a whole, runs at low temperature.

Over the last few years the observation by manned submersibles of active springs and their seafloor precipitates has been the most successful technique for studying seawater-rock interactions. Additional information has come from studies on dredged rocks, in deep-sea drill holes, and in ophiolite suites. These types of observations need to be related by thermodynamic analyses. In addition, experimental studies of the seawater-rock interaction should attempt to simulate more precisely the effects of open-versus-closed-system reactions on both the solid and fluid products.

Three new areas need development. First is the long-term observation of the active hydrothermal springs using multi-instrumented deep-ocean packages that can be deployed for times of between 1 month and 1 year. Such instruments will permit the investigation of the time-averaged properties as well as shorter-period variations. Second, accurately placed drill holes in and near these vents will permit investigation by subsurface instrumentation. This approach will require some additional technical development because of the current difficulty of drilling holes on active mid-ocean ridges; techniques for drilling on bare rock need improvement. Third, existing technology allows penetration of hard rock on a sediment-buried ridge axis. These axes should be drilled. While the crustal section may not be representative of the open-ocean system, the information gathered will significantly improve our understanding of sediment-hot rock interactions.

The dynamic nature of the mid-ocean ridge is well established. An interdisciplinary effort, Ridge Interdisciplinary Global Experiment (RIDGE) funded by ONR, NSF, NOAA and the USGS, is now beginning to focus on specific sites to document either the rates of change in system components, or the interactions linking the physical, chemical, and biological processes that occur at the ridge axis. One of the major efforts of the academic community will be to examine one or two ridge axes in detail. These studies will measure and then model temporal and spatial covariation among processes involved in the generation and evolution of the ocean floor. The technological and intellectual stimulation involved in the successful implementation of such natural seafloor laboratories will provide a new generation of dynamically based, quantitatively testable models of ocean crustal generation.

They, in turn, will improve our understanding of the biological and chemical consequences of the generation and evolution of the crust. Ultimately, these models will yield a much improved understanding of the structure and surface morphology of the entire ocean basin.

Role of the Ocean Through Time

The crustal processes described in the preceding three sections result in the formation and evolution of the ocean basins. The sediments that cover the floors of the basins record the history of the oceanic environment and events on the neighboring continental masses as the basins evolve. The principal types of sediment found in the deep ocean and their distribution were defined by the results of the cruise of H.M.S. Challenger a century ago. As a result of subsequent work, the nature of Quaternary ocean sediments and their distribution on the sea floor are reasonably well known and the controlling factors understood, at least in broad terms.

Paleoceanography

A major development of the last 20 years has been the advent of scientific ocean drilling, permitting investigation of the early sedimentary record. Between 1968 and late 1983 the Deep Sea Drilling Program (DSDP) drilled a total of 1092 holes at 624 sites between the latitudes of 76°N and 77°S, with the deepest hole penetrating more than 1700 m into the seafloor. The work initiated by DSDP is now being continued by the Ocean Drilling Program (ODP) using a newer drilling platform with more advanced technology and offering the promise of deeper holes and holes in formerly inaccessible locations.

Of the many areas of the earth sciences affected by the results of scientific ocean drilling, certainly none has been influenced more than studies of oceanic sediments and the interpretation of the sedimentary record in terms of the changing ocean environment (paleoceanography) (Figure 3-8). Indeed, paleoceanography can be said to be a whole new field of endeavor spawned by DSDP. Drilling tests this concept, in turn providing a simple model that can be used to interpret the drilling results. Not only have the drilling results shown that the geometry of present facies can be interpreted, they also permit us to go further and explore the history of changes in the depth of the carbonate compensation surface. The method of backtracking along the age-depth curve to determine paleodepths of a location at times corresponding to facies changes or other important geological events is now an established procedure.

An important and surprising result of biostratigraphy of DSDP cores has been the recognition of major hiatuses of regional extent in the sedimentary record in all the ocean basins. Often these hiatuses can be recognized only from breaks in the biostratigraphic record or from the occurrence of undatable intervals over which the net sediment accumulation rate abruptly decreases to near zero. In some places, particularly around the ocean margins or in shallow water, gaps in the sedimentary record may be attributable to uplift and erosion, or to changes in the local balance between sediment supply and the processes operating to remove and redistribute it. However, the lack of sediment accumulation in deep water over areas representing major fractions of the ocean basins is more problematic. On an ocean-wide scale, the spatial distribution of hiatuses can be interpreted in terms of patterns of bottom water circulation. The temporal and spatial distribution of hiatuses shows a general trend toward increased frequency and abundance of hiatuses in the older parts of the record, and considerable variation in hiatus abundance between adjacent periods. The general trend can be interpreted in terms of a comparatively simple model for sedimentary



FIGURE 3-8 DSDP sites plotted on an early Oligocene reconstruction of the Indian Ocean. Open circles represent sites where the sedimentary section is complete, solid circles where there is a proven unconformity, and half circles where there is an undated interval or an inferred unconformity. The shading indicates the extent of the Oligocene unconformity; cross-hatching shows the extent of the proven unconformity (Davies, 1985, by courtesy of Macmillan Journals, Limited).

recycling, while the superimposed variations between adjacent time periods are believed to reflect changes in global oceanic circulation patterns. These paths, and even the rates, of bottom circulation are related to the sizes, shapes, and locations of the ocean basins and their interconnections—features that, as a result of plate tectonics, have changed.

The problem of reconstructing the environmental history of the oceans can be approached from a regional or a global perspective. Neither is feasible without results from ocean drilling. The regional approach simply takes all of the known data about a region and attempts to infer from them information about the environmental history. The fact that the oceans do not consist of discrete, isolated regions places a serious limitation on regional studies, for generally the region under consideration is continually influenced by outside events. An alternative approach is to examine the data on a global scale, in the hope of detecting gross environmental trends, the local details of which can then be elucidated by regional studies. In the past this approach has not been possible because of the lack of worldwide geologic information about the ocean basins. The global coverage of deep-sea drilling sites, however, opens up new and exciting possibilities, which we are only now beginning to appreciate.

In terms of investigating sedimentary infill of the ocean basins, areas that must be

addressed in the future include the high northern and southern latitudes and the ocean margins. With the new drill ship available to ODP, southern ocean drilling is a major part of the present program. The extremely thick sediment cover and the potential for encountering hydrocarbons, however, continue to preclude many ocean margin areas from scientific drilling. This situation is unfortunate, for it is the sediments covering the passive ocean margins that hold the record of the earliest stages of rifting and the subsequent development of the ocean basins. Without this part of the record, our understanding will be forever incomplete.

Deep-Sea Sequences

Another area of the sedimentary record poised for major advances in the next decade is the understanding of deep-sea sedimentary sequences. Hydraulic piston cores gathered by drill ships have substantially increased the duration of undisturbed sedimentary sequences available for a variety of research efforts. Two such research areas seem most promising: paleoclimatic and evolutionary studies.

Detailed studies of past climatic or paleoceanographic variability, heretofore restricted to conventional piston cores 10 to 20 m in length, can now be extended to sequences over 200 m long. As a consequence, the detailed history of late Neogene global climates can be read. This opens the door to understanding how climate varied when the boundary conditions of the climate system were substantially different from today's. For example, one can determine how the climate system varied in the absence of an ice cap on Greenland or with an open seaway through Central America. Studies of Pleistocene climate have focused on the cyclicity of the advance and retreat of northern hemisphere glaciers. The timing of these major changes seems to be controlled by changes in the geometry of the earth's orbit. If so, then these forcing periods should extend back through all of geological time and may have left an imprint on the sedimentary record. Since ice ages occurred during the late, and not the early, Cenozoic, the response of the climate system to this forcing must have changed. This changed response must have been caused by some change in the climate system's boundary conditions, e.g., atmospheric circulation or composition, or solar output.

The record of these changes in the climate system's boundary conditions will be recorded in the sediments and can be read from changes in frequency or amplitude of the quasi-periodic response to orbital forcing, or by one-way step functions that correlate with, for example, global ice volume and sea surface temperatures from O_{16} to O_{18} ratios in high latitudes.

A second method that will be useful in this effort and has been applied selectively to deep-sea drill holes is wire line in situ specialized measurement devices called logs. In high latitudes such as the North Atlantic and Antarctic, where rapid sedimentation provides sufficient resolution, climatically induced layering causes a periodic change in acoustical properties of sediments. Acoustical logs of these sediments reveal cycles with periods similar to those of orbital variations. Since logging represents data acquisition that is highly resolved in geologic time, and the log's record is continuous, it should be possible through the analysis of logs from many holes to gain important information on the regional frequency and amplitude response of the climate system to orbital forcing. Also, one should be able to resolve changes in the climate system's boundary conditions.

These climatically induced variations of acoustical impedance are an important part of the acoustical character of the upper few hundred meters of ocean floor sediments. Their study will help make accurate maps of regional variations of the acoustical properties of deep-sea sediments.

Higher-resolution logging devices are now available that can resolve orbital frequency variations in sedimentary sequences with lower sedimentation rates, such as those found in low latitudes. The academic community needs to add a high-resolution logging device to the drilling vessel Resolution in the very near future, so that this important high-resolution acoustical information can be gathered from a global array of drill sites. This work would complement the current ONR-supported programs, which already include both direct measurement of shallow sediment reflectivity and sophisticated modeling capability, including estimation of shallow velocity gradients and attenuation. It will be supplemented by study of sediments accessible by piston cores, with greater resolution than that obtainable with sonobuoys. Documentation of high-resolution porosity variations near the seafloor is advancing rapidly because the orbital forcing function is known for any geologic age. Extrapolation of porosity variation from one depth to another through decompaction is straightforward, and NRL already has established the relation of porosity to velocity for shallow sediments. Near-seafloor velocity fluctuations occurring on a vertical scale of centimeters can have a major impact on seafloor reflectivity, by partitioning incoming sound energy in the 3.5- to 12-kHz range into short-path multiples.

A second opportunity that is now available through hydraulic piston coring is the chance to carefully document the evolutionary steps that led to the modern shelled planktonic flora and fauna. Documenting evolutionary transitions and migrations in fossil populations on a global scale has been difficult and has led to much controversy on the rates of these changes. It is known, however, that evolutionary transitions between species can be observed in deep-sea sediments. Hydraulic piston cores now provide an ever-growing global array of sites to monitor the evolution of shelled microfossils over the last 10 million to 15 million years. This kind of work should and probably will be a major effort during the next decade.

Sediment Dynamics and the Benthic Boundary Layer

The central issue in sediment dynamics is the quantitative prediction of modes, frequencies, and rates of sediment transport, along with gross reworking and net erosion and deposition depths. Erosion and deposition result in topographic changes on scales of meters in time scales of weeks. Sediment dynamics is inherently complex. Not only is it interdisciplinary (involving boundary layer fluid mechanics, sedimentology, and organism effects), it is also nonlinear and episodic, with most transport occurring once a month or once a year (Figures 3-9 and 3-10). Spectacular advances recently have been made by focusing theory and new measurement technologies on specific environments deliberately chosen to be at, but not beyond, the limits of complexity with which sediment transport models can deal.

For example, the High Energy Benthic Boundary Layer Experiment (HEBBLE) Program chose a region of simple bottom topography at the base of the continental rise, where simple one-dimensional models of sediment transport could be tested. At the time the program was formulated, no testable theory could deal effectively with wave and current interactions with the bottom, and so shelf depths were avoided. HEBBLE spawned diverse new measurement technologies capable of resolving the full spectrum of length and velocity scales that critical testing of theory demands. Not only has this testing succeeded in verifying a quantitative model, but it also has revolutionized thinking about energy levels of near-bottom flow and their unsteadiness in the deep sea. HEBBLE discovered that ripples parallel to the current are deposited in weeks to months from dense suspension when strong transport events subside. Finding these bedforms in many deep-sea regions suggests that HEBBLE's results may be widely generalized. They certainly are applicable to those large

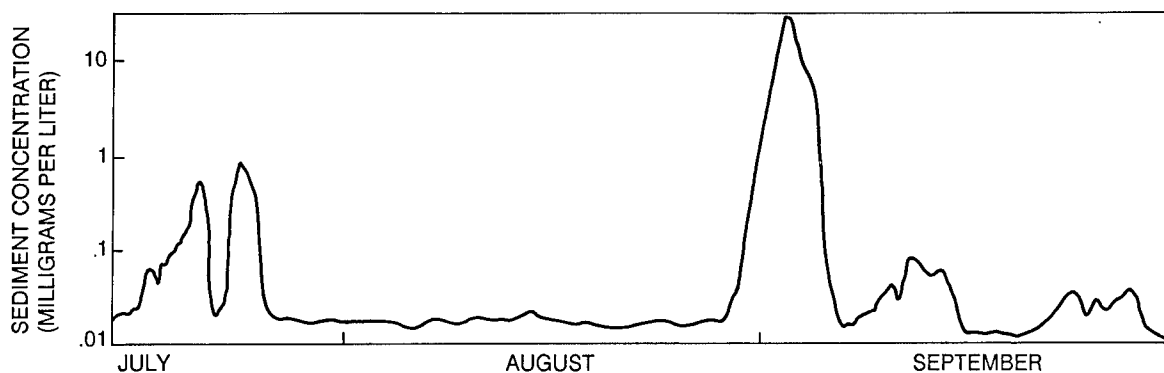


FIGURE 3-9 Sediment concentration varied by a factor of nearly 1000 at 1 m above the ocean floor over a 10-week period at the HEBBLE site. Peak concentrations coincided with severe storms at the base of the continental rise in late July and early September.

areas along western sides of ocean basins where strong density-driven thermohaline flow couples to areas of high eddy-kinetic energy.

Since HEBBLE's inception, theoretical understanding of sediment transport in more complex flows in shallower water has advanced dramatically, notably in the area of wave and current interactions with the bottom. These new models already have been applied, albeit in semi-empirical fashion, to the complex environment of surf zones. Here, currents, alongshore infragravity waves, onshore gravity waves, and topography interact. Accessibility, the noncohesive nature of beach sediments, and clever new measurement technologies offset this complexity in the physical forcing, so major advances are now being made. One of the real surprises has been the importance of even very low amplitude infragravity waves in modulating sediment transport, ignition (liftoff) rates, and control of beach topography.

A conclusive field test of high-energy (storm-driven) wave and current bottom interaction models and of predicted sediment transport consequences (Sediment Transport Events on Shelves and Slopes [STRESS]) has been initiated by ONR. It was motivated by preliminary results from NSF's CODE that give reason for optimism about the quality of the models in understanding fluid forcing and the resulting flux of sediment and by the success of HEBBLE in dealing with a simpler environment. In this regard it is important to recognize the great variation in input/output/storage terms of sediment on the shelf from and to rivers, estuaries, and beaches. A continental shelf program aimed at a conclusive test of bed response is the logical next step in the progression from the physical simplicity of the HEBBLE environment. Much of the needed technology has already been produced within the HEBBLE and surf-zone programs.

An especially interesting subset of shelf and upper-slope environments that may provide insight into sedimentary processes over more complex topography (e.g., seamounts) are at shelf edges. Preliminary observations suggest strong interaction of currents, surface waves, and internal waves with the bottom and hint that the idea of relic shelf-edge sands out of equilibrium with the present flow climate may need revision. High-resolution Gloria, SEABEAM, and SEAMARK surveys of shelf-edge environments further suggest that turbidity flows at shelf edges and upper slopes may be frequent enough to allow correlation with ignition mechanisms. Post-ignition events lately have yielded to theoretical modeling and laboratory experimentation, but prediction of frequency and intensity as functions of environmental variables remains elusive.

As knowledge of specific environments has progressed, it has become apparent that

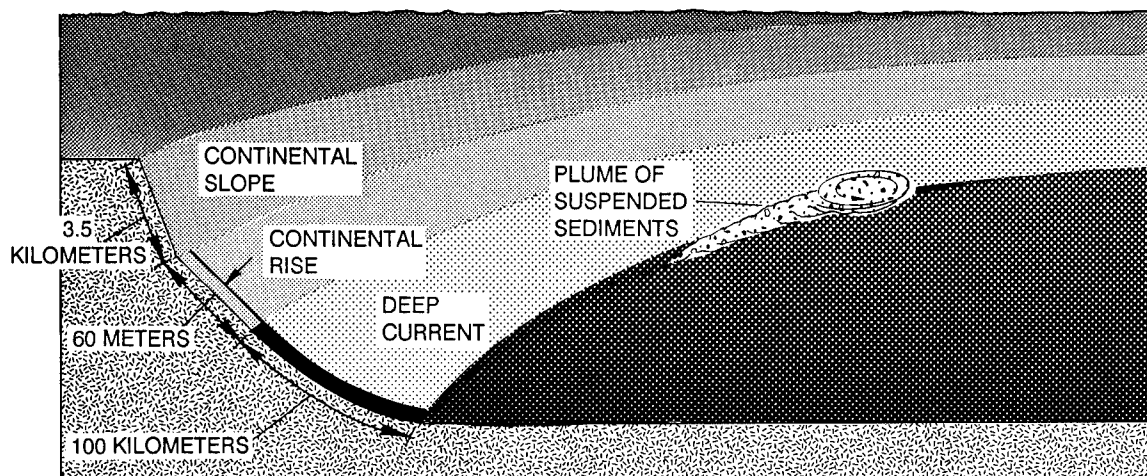


FIGURE 3-10 Mesoscale eddy is depicted schematically as it interacts with the southward-flowing abyssal current at the base of the continental rise 450 miles off the New England coast. The current is pressed against the rise by the Coriolis force. Such eddies, or storms, appear to be correlated with the presence at the sea surface of mesoscale eddies shed by the Gulf Stream. The abyssal eddy takes the form of an ellipse about 30 km long and perhaps 5 km wide; its height has not been established. The coupling of the eddy and the mean abyssal current scours the bottom, entraining mud that is swept downstream and is subsequently redeposited in sediment drifts.

particular processes require greater attention. For example, there is much more detailed theory and controlled observations on erosion than on deposition, at least in part because the latter process is more difficult to simulate and to measure accurately. Only recently have data on critical shear stresses for deposition of fine particles been obtained, and they show the speculative Hjulstrom plot that is widely used to be in error by two orders of magnitude for the current velocity at which particles of 2 to 20 μm (rough average of ocean particle sizes) will deposit. Another basic issue in marine sedimentation is the form of the sedimenting particle. Most particles arrive at or approach the seafloor in some form of aggregate, yet aggregates are poorly characterized dynamically. Nor do we know whether the net effect of the strong shears on natural marine aggregates in the lowermost part of the bottom boundary layer is additional aggregation or even disaggregation.

A related issue is the knotty problem of predicting cohesive/adhesive sediment transport in a way that will generalize from one environment to another. The mechanical (geotechnical) properties of mud are complex and time dependent, even without biotic influence, and are strongly influenced by organism activities. How and to what extent geotechnical parameters can be used as predictors of transport and behaviors is not yet clear; any successful attempt will have to be strongly interdisciplinary.

NAVAL RELEVANCE

Issues associated with submarine operations and ASW have dominated discussion of naval MG&G relevance for the last several decades and show no sign of diminishing in relative importance. The questions, however, have shifted and become more subtle both as a result of improved knowledge of bottom characteristics and as the nature of the threat has changed. The major efforts in ASW are toward lower frequencies for both active and passive detection, to distributed fields of sensor arrays, and to renewed interest in marginal seas and coastal zones.

In addition to continued traditional concerns with issues of bottom scattering, absorption, and reverberation, these efforts imply substantially increased interest in sub-bottom acoustic propagation and its variation as a function of frequency and direction, particularly at low acoustic frequencies. Coupling between water and sub-bottom wave guides, the influence of morphological variations on propagation and attenuation and similar issues are becoming of greater relevance as the Navy investigates new detection techniques. There also is an increasing need to understand the differences in performance of different sensor types, both to elicit information on the nature of propagation and to optimize detection capabilities. Fundamentally, the operational requirement is to move away from merely descriptive treatments of bottom interactions. An ability to model low-frequency (in the 0.1 to 400 Hz region) signal and noise for on- and sub-bottom sensors is rather urgently required to assist in the applied research and development of ASW systems. The modeling requires more fundamental understanding than is now available.

While operational ASW interest and associated MG&G research have properly emphasized the deep ocean, there is now a strong rationale for augmenting that work with studies of margin-limited environments. Both our own maritime strategy and the likelihood of increased Soviet submarine activity near our continental margin imply long-term interest in coastal operations. The known difficulties of traditional shallow-water acoustics imply a need for innovative structural and propagation research on the shelf to improve our understanding of the transmission of acoustic and elastic waves in the region.

Coupled with the need for improved understanding of signal and noise and their propagation at and beneath the seabed is increased interest in the bottom terrain itself. Again, this interest applies to continental margins as well as to the deep ocean, and extends beyond general descriptive information to detailed, quantitative characteristics of physical, magnetic, chemical, and electrical properties and geomorphological processes. There are intriguing parallels between land and sea warfare that cannot be fully evaluated without such enhanced understanding.

The Navy also has a major continuing interest in sedimentary processes. In addition to the dominant impact of bottom dynamics on nearshore operations (e.g., amphibious landings, mining, and mine countermeasures) and ocean engineering (e.g., ports, harbors, channels), there is an increasing concern with bottom stability on the shelves and in the deep ocean. It is largely driven by the transition from individual arrays to distributed systems, and the associated advent of fiber optic cables. A significant increase in both the amount and vulnerability of seabed cabling, coupled with an appreciation of the dynamic nature of the deep seabed revealed by HEBBLE, mandates major concern with the nature of sedimentary processes and shelf-slope stability.

In general, then, the relevance of MG&G to naval operations remains strong and is expected to increase. While recent research has yielded survey capabilities that will substantively improve the quantity of available information, there remain driving issues of processes and fundamental questions of basic physical characteristics that require attention. Finally, recent advances in understanding processes of crustal creation at mid-ocean ridge axes offer the exciting prospect of probabilistic predictions of crustal parameters at spatial scales of interest to surveillance systems. Continued research into the processes by which crust is emplaced at the ridge crest and is subsequently modified by faulting, injection of magma, and hydrothermal alteration is expected to lead to the ability to infer from remotely sensed data the magnitude and variance of sub-bottom effects along arbitrarily specified paths, even in sediment-covered regions. Such basic research efforts, which can increase substantially our knowledge by enabling us to *predict* (and verify) instead of just *measure*, are extremely important from both fiscal and operational perspectives.

CURRENT PROGRAMS

The present Geology and Geophysics Program can be broken down into three components: core, the G&G component of the Shallow Water Acoustics ARI, and the Southern Oceans ARI.

Core Program

The objectives of the core program are (1) to understand the history and dynamics of the physical processes that form the crustal and sediment layers and that modify their characteristics in oceanic areas of interest to the Navy and other Department of Defense (DOD) components; (2) to use existing background information to select critical areas in which field experiments can examine the physical characteristics of the bottom, sub-bottom, and boundaries; (3) to develop an understanding of the role that the ocean bottom plays in the propagation of acoustic energy in order to understand the genesis of various types of large-scale bathymetric features, and their relationships and control on the distribution and character of small-scale and fine-scale bottom features; (4) to develop techniques for analyzing variation of gravity and the resulting geoid; and (5) to examine the response of the ocean bottom sediments and their modified physical characteristics to imposed stresses produced by currents and biological processes in the benthic boundary layer.

Shallow Water Acoustics

In contrast to deep-water propagation, where purely waterborne acoustic paths predominate, shallow water paths interact many times with the bottom. Shallow water acoustic propagation is thus very sensitive to the properties of the sediment and subbottom. The properties of shallow water sediments are highly variable, both vertically and horizontally; consequently, investigations of acoustic propagation must consider both deterministic and stochastic phenomena. Recent data suggest that the depth and frequency dependence, and even the order of magnitude, of compressional wave attenuation in sediments are poorly known, as are the magnitudes of the speed and attenuation of shear waves. While there has been much progress in modeling stochastic scattering phenomena for deep-ocean seismic propagation, this approach has yet to be emphasized in the geologically more complex shallow water environment. Substantial theoretical and experimental effort is needed to provide estimates of the effect of statistical variations in the sea bottom on the propagation and coherence of sound in shallow water. To do so, the geologic parameters that influence shallow-water sound propagation must be isolated and the precision to which they must be known has to be established.

Southern Oceans Research

This ARI is a multidisciplinary basic research program emphasizing physical oceanography and marine geology and geophysics. The main research objectives of the geology and geophysics portion of the program are (1) to locate sediment source areas, identify sediment distribution patterns, and understand sediment dynamics in the Argentine Basin; and (2) to quantify crustal heterogeneity in the Southern Ocean and relate it to theories of crustal evolution. Fiscal year 1988 will be the final year for this ARI.

PROMISING RESEARCH TOPICS

This is a time of exceptional scientific opportunity for the earth scientist. The first section of this chapter described the changing definition of the discipline of marine geology and geophysics. This change has resulted from the advent of a new generation of instrumentation (such as ocean bottom seismographs, MCS profiling systems, SEABEAM, SEAMARC, GEOSAT) capable of taking data with far greater temporal and spatial resolution at expanded temporal and spatial scales than could have been imagined in the context of classical MG&G. Rather than attempting a comprehensive list of all the scientifically interesting research areas that exist today, we discuss below several major topics that are not only at the forefront of modern MG&G but also hold special interest for the Navy. All will require the hypothesis-based, multidisciplinary approach to MG&G that characterizes these increasingly process-oriented subdisciplines.

Global Ocean Sciences—Marine Geology and Geophysics

Two important programs in marine geology and geophysics are currently in the early stages of planning and funding and involve a broad spectrum of oceanographers. These two projects, RIDGE (Ridge Interdisciplinary Global Experiment) and a Continental Margins Initiative, are sponsored by the National Research Council's Ocean Studies Board. They are characterized by broad interdisciplinary interest and support (marine chemistry, marine geology and geophysics, biological oceanography, continental geology, and oceanography), multiagency coordination and funding (NSF, NASA, ONR, NOAA, and the USGS), and durations of at least a decade. These programs were discussed broadly by the ocean principals as part of the projected studies in global ocean sciences and form a portion of the Global Ocean Sciences Program (GOSP). The two programs are extensive, and funding and support by any single agency is simply not possible. The panel recommends that ONR assume a major role in these studies and that specific aspects of the programs be selected to ensure that relevant Navy laboratories play an integral role in the research.

The continental shelves and margins are areas for promising future academic research. In addition, they are regions of probable increases in Soviet submarine activity and have historically been problem areas for acoustic ASW systems.

Integrated use of modern bathymetric mapping systems and MCS reflection systems in focused experiments should lead to significant improvements in our understanding of margin structure and evolution. Such an effort should be closely coupled with a study of acoustic and elastic wave propagation at the continental margins, especially including the shelves. The long-term product for the Navy would be an ability to predict the effect of bottom interaction on acoustic and elastic waves (at frequencies down to 1 Hz) along with specific propagation paths in bottom-limited regions.

The mid-ocean ridges present optimal locations for broad interdisciplinary research. The bulk of the earth's crust and lithosphere is generated at these volcanic centers and the circulation of hydrothermal fluids through the upper crust is an important buffering mechanism for the chemistry of the world's oceans. This circulation is, in many respects, as important as continental runoff. The injection of tracers into the water column is useful for studying the deep circulation of the oceans and the ridges, and associated fracture zones control the global circulation of bottom waters. Chemosynthetic bacteria, living in very high temperature environments, support an extensive and unusual food chain. Vent communities may be quite isolated, and evolutionary pressures may serve to produce variations at the DNA level that could be useful in refining the precision of geologic timing. Not only does mid-ocean ridge biology capitalize on the chemical exchange of hydrothermal circulation,

but the bacteria and vent dwellers themselves play a role in modifying the geochemistry. Although hydrothermal circulation is unlikely to play an important role in ocean circulation, some investigators were rhapsodic in interpreting the importance of major events such as the Juan de Fuca Ridge "megaplume" which apparently arose from a major event on a spreading center.

The mid-ocean ridges, from the point of view of marine geology and geophysics, are fundamentally important. Although these important features are global in extent, the ridges appear to be passive responses to substantial tensile tectonic stresses. This passivity leads to impressive regional feats of agility in jumping locations and propagating in changing directions. Fast-spreading ridges seem to have intracrustal magma chambers, but slow-spreading ridges have typical oceanic crustal sections. Quantification of the properties of these ocean ridge structures has only begun and will require intensive morphological characterization as well as detailed travel time, waveform, and electromagnetic experiments in order to understand the processes.

The ONR should be particularly interested in development of multipurpose seafloor observatories and autonomous seismic and electromagnetic stations required in the experimental effort. The Arctic Ocean is dominated by very slowly spreading ridges and fracture zones, and the development of relevant technologies for exploring this environment should be pursued. Analysis, modeling, and interpretation of existing data, as well as acquired data, are required and could be initiated immediately. This effort would require access to supercomputers and interactive work stations in order to be carried out effectively.

Continental Margins

The continental shelves and margins have been identified as future areas of promising academic research. In addition, these areas—regions of probable increase of Soviet submarine activity—have historically been problem areas for acoustic ASW systems.

Future academic research through NSF is likely to concentrate on structure and composition at full ocean depths. Thus, the NSF-funded programs will not resolve the issues of propagation and structure in areas (shelf and margin) of great Navy interest. With a strongly focused program funded by ONR, however, it is unlikely that the academic community will bypass investigation of water depths less than 1 or 2 km.

In view of the structural complexity of continental margins, it may be appropriate to consider selecting a particular region as a "natural laboratory" in which to conduct a diversified suite of seismic measurements designed to characterize propagation in the shallow water environment. For example, in the Gulf of Mexico, significant in situ data can be obtained from wells already drilled, and the possibility also exists for instrumenting wells for specific programs. Vast amounts of MCS data already exist there and may prove extremely useful as a supplement to a quantitative characterization effort. The relevant Navy objectives of these measurements would be to determine the field measurements most useful in predicting propagation in the shallow water environment.

This effort should be augmented by site-specific studies in regions of particular Navy interest such as the North Slope of Alaska, the Bering Straits, the east coast of the United States, and the Barents Shelf.

A significant data analysis, modeling, and interpretation effort using existing and acquired data will be required and could be initiated immediately. This effort would require efficient access to supercomputer facilities and interactive work stations.

Mid-Ocean Ridges

The study of mid-ocean ridges is currently a very high priority within the academic community and great progress in our understanding of crustal genesis is being made with each new expedition. The mid-ocean ridges are of great interest within the Navy since all the ongoing tectonic and extrusive processes that determine the shape and structure of the ocean crust in the deep ocean basins take place at the ridge axis. Furthermore, because time scales of even decades characterize these geological processes, mid-ocean ridges are the sites of the highest rates of tectonism, earthquake activity, and chemical and energy interchange, as typified by the dramatic hydrothermal vent fields to be found in the deep ocean basins.

The study of the mid-ocean ridges requires the intimate interaction of all disciplines in oceanography. The mid-ocean ridge dominates the earth's volcanic flux and creates an average of 20 km^3 of new oceanic crust every year. The processes of generation and cooling of oceanic lithosphere contribute two-thirds of the heat lost annually from the earth's interior. One-third of the heat flux in oceanic lithosphere is carried by the circulation of seawater through fractures in hot oceanic crust. This hydrothermal circulation facilitates a major chemical exchange between seawater and oceanic crustal rocks that acts as an important regulator of the chemistry of the oceans and of the volatile content of the earth's interior. Major vent fields provide the energy and nutrients for the support of diverse communities of organisms sustained by a unique food chain based on chemosynthetic bacteria. Not only are these organisms profoundly influenced by such hydrothermal circulation, but the vent communities in turn have a marked impact on the physical and chemical environments they inhabit. These unusual forms of life may provide a clue to the origin of life on earth.

The Ocean Studies Board, as noted earlier, sponsored a workshop on the mid-ocean ridge at the Salishan Lodge in Oregon in 1987. The workshop participants endorsed the creation of a new organization in order to pursue actively progress in the study of these important features. The organization has been named RIDGE and has adopted the goal of understanding the physical, chemical, and biological causes and consequences of energy transfer within the global ridge system through space and time. The organization has adopted six objectives:

1. to understand the flow of the mantle, the generation of melt, and the transport of magmas beneath mid-ocean ridges;
2. to understand the processes that transform magma into ocean crust;
3. to understand the processes that control the segmentation and episodicity of lithosphere accretion;
4. to understand the physical, chemical, and biological processes involved in the interactions between circulating seawater and the lithosphere;
5. to determine the interactions of organisms with physical and chemical environments at mid-ocean ridges; and
6. to determine the distribution and intensity of mid-ocean hydrothermal venting and the interaction of venting within the ocean environment.

Seagoing expeditions, laboratory studies, and theoretical and large-scale computing experiments will be required in order to solve existing problems.

Low-Frequency Acoustics

Measuring the thickness of the oceanic lithosphere as a function of age and how this thickness varies with position is necessary to understand the relation between the lithosphere and the convection system below. The academic community is developing seafloor

instrumentation capable of operation at extremely low frequencies to measure this thickness and investigate these relations. In the past, little attention has been paid to the propagation of energy at seismic/VLF acoustic wavelengths (1 to 100 Hz). The Navy is increasingly interested in possible exploitation of VLF acoustic energy because the Soviets have learned, as the United States did a couple of decades ago, that reducing high-frequency noise on submarines is relatively straightforward and not overwhelmingly expensive. Reducing low-frequency signals from ships and submarines is fundamentally more difficult. Future ASW sonars will increasingly rely on transient low-frequency signals, familiar ground for academic seismologists.

While acoustic and elastic waves can be treated as only loosely coupled when they propagate in water deeper than a few wavelengths, that assumption becomes more unacceptable as depth approaches acoustic wavelength. At VLF wavelengths, much of the ocean becomes "shallow," and the effects of bottom interaction on energy propagation must be accounted for by a full wave-field model; the bottom interaction must be accounted for in *any* bottom-mounted array, in order to allow phase-coherent processing. Understanding VLF propagation requires research into the variation of noise and signal levels as functions of sub-bottom depth, the frequency and wavenumber content of both VLF signals and noise, and modeling the propagation of VLF energy along range varying paths.

In addition to the unknowns described above, there is a lack of knowledge concerning seafloor scattering effects and their influence on signals and noise and of noise sources at frequencies from 10 mHz to 5 Hz. Suspected noise sources are atmospheric fluctuations and ocean turbulence. Fully quantitative models of seafloor noise require deterministic rather than empirical models for transfer of momentum from winds to the oceans and the resultant frequency and wavenumber content of the resultant gravity waves. This aspect of a well-defined research program requires a strong interdisciplinary component. To address this wide range of fundamental questions, the panel recommends a research program in which the theoretical modeling of wave propagation is supported by an extensive field program. This field program would involve state-of-the-art towed and bottom-mounted instruments, including electrical conductivity instruments, which are well suited for measurements of horizontal displacements at the seafloor. In addition, the field program should take advantage of the sophisticated instrumentation being developed to support the ODP and NSF's recently proposed RIDGE Program.

It should be noted that although seismic and acoustic experiments in shallow water are attractive from a cost point of view, the certain differences between deep and shallow water noise processes, and consequent estimation of signal-to-noise ratios, require strong experimental programs in both areas.

Sediment Dynamics

There is no model of sediment dynamics that predicts modes, frequencies, and rates of sediment transport, erosion, and deposition on the seafloor. The lack of such models prevents interpretation of seismic stratigraphic horizons on the continental shelf and in the deep sea. The growing relevance of this problem to the Navy arises from the prospect that future ASW sonar systems will increasingly involve large arrays of bottom-mounted sensors and their associated cables, both on the continental shelf and in the deep sea.

Recent theoretical advances in shallow-water sediment transport lead us to recommend a new program to merge the new theory with the results and instrumentation developed in HEBBLE. This program should be conducted both on the continental shelf and in the deep sea. Opportunities exist in such a program for major advances in the mechanics of

particle aggregation and deposition, and in our knowledge of seasonal patterns of biological effects on the sediment transport process. The importance of these scientific issues becomes paramount on the upper continental slopes, the shelves, and the nearshore regions, which are those portions of the continental margins where VLF acoustic energy will be most subject to bottom interaction. Research into these topics must closely couple process-oriented modeling with field studies, since it is important for naval applications as well as for scientific understanding that we know to what extent results from one region can be generalized to others.

It is likely that several kinds of environments will have to be studied in a reconnaissance mode before one or a few can be selected for detailed experimentation. Because of the high relevance of the Arctic to the Navy, the panel suggests that at least one high-latitude site be considered.

Quantitative Mapping and Geomorphology

How seafloor spreading occurs at active ridge crests determines the structure, and it is believed that if these processes can be described correctly at the ridge axis, the relationship between compositional variations and surface morphology will be understood. As a result of this understanding, it should be possible to predict the composition and structure of the ocean floor in the rest of the oceans on a scale of 1 to 2 km without having to survey it. This ability to relate high-resolution bathymetry to subsurface structure and acoustic-seismic properties will provide the research community and the Navy with a cost-effective use of finite survey resources.

The panel recommends that ONR initiate a research program directed at exploiting the potential of new survey tools (such as SEABEAM, SEAMARC, and GEOSAT) for indirectly measuring important geophysical parameters accurately and precisely over large areas. For example, today the primary end product of a SEABEAM survey is a color contour map of bathymetry, even though much quantitative information about topography-dependent processes (such as elastic/acoustic wave propagation) is implicit in the backscattered acoustic energy. Research is needed first into techniques by which properties that affect acoustic propagation and gravity response, such as roughness, vector length scales of topography, and regional trends, can be robustly inferred from the actual measurements over the survey swath. This effort should be followed, when appropriate, by investigations of the extent to which such properties can be extrapolated into regions outside the actual surveyed swath.

In a similar vein, the panel believes that the capability to construct global maps of regional bathymetry to 5-km-length scales is within reach, through the development of geoid/topography transfer functions that could be applied to GEOSAT altimetry data referenced to a relatively few, precisely navigated SEABEAM or possibly SEAMARC lines. Besides the prospect of developing a survey capability for inaccessible areas, research into this possibility would build on recent advances in our geophysical fluid dynamical modeling of the thermal boundary layer and would provide the opportunity for fundamental advances in our knowledge of how the earth functions as a geodynamical system.

Structure and Formation of the Arctic Basin

From a geodynamic perspective, the Arctic is an area of considerable research interest because it is the one major area in the oceans where structure, age, and tectonic history are still unknown. Further, we note that geological processes dominant in the Arctic are

significantly different from those at lower latitudes where most research has been carried out.

For example, sediment dynamics in regions that receive predominantly glacially derived terrestrial input, and in which the shelves may have been subjected to shaping by the glaciers themselves, may be significantly different from our more familiar models. Similarly, the frequency and intensity of storm events is different from that at lower latitudes, and this too may lead to effects that cannot be reliably predicted. The Arctic, especially the North Slope of Alaska, the Bering Straits, the Georges Basin (west of the Alaskan continental mass), and the Barents Shelf, is a particularly attractive area where three of the research initiatives discussed earlier in this section could be carried out. For example, MCS studies of the shallow and deep structure around Alaska could yield (1) significant information on passive margins (North Slope transect), (2) continental interaction during phases of compression (Bering Straits transect), and (3) transform fault deformation (Barents Shelf study). In addition, sediment dynamics studies in shallow water in the Arctic would provide a high-stress test of models developed in coastal regions. The surface boundary conditions and temperature problems in the arctic differ fundamentally from those in the open ocean, and for this reason the Arctic provides a unique opportunity for studying the excitation of both ULF and VLF noise in the water column and on the seafloor. Finally, passive, low-frequency seismic studies in the Canada Basin could determine the structure and lithospheric thickness of the oceanic plate in this region.

The Arctic includes the continental shelf of the United States and Canada closest to the Soviet Union. In addition, Soviet submarines must pass through the Barents Shelf region in order to reach the North Atlantic from the north. These facts make this an area of great importance to the Navy. In view of the high Navy interest and the exciting science opportunities, the panel suggests that ONR initiate a program of focused MG&G research in the Arctic.

A dedicated data collection effort concentrated on a series of areas is warranted by the importance of the physical processes outlined previously. From a scientific perspective, the panel believes that the Bering Straits and Shelf should have the highest priority. It is recognized, however, that the Barents Shelf probably has the highest priority for the Navy. Thus, the panel suggests that a long-term program to contrast and compare the basic shallow structure and sediment dynamics of both these regions be considered by ONR.

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4

Oceanic Biology

Oceanic biology crosses the boundaries of marine biology, marine ecology, and biological oceanography. Marine biology and ecology usually use marine organisms, populations, and communities as model systems for the study of general physiological and ecological processes. Biological oceanography, on the other hand, has as its goal the identification and understanding of processes controlling the abundances, kinds, and temporal and spatial patterns of variations of organisms in the sea. The trend in the Oceanic Biology Program is to concentrate on those portions of the biological oceanography goal that are relevant to the Navy, dividing work on physiological aspects of marine organisms with the Biological Sciences Directorate. In other words, the focus of oceanic biology program comprises those aspects of biology at the individual organism, population, or community level that entail interaction with other marine organisms and with the physical, chemical, and geological environment.

TRENDS AND RECENT PROGRESS

Primary Production

The process of primary production by phytoplankton is the intellectual center of biological oceanography. Independent means of estimating its magnitude have shown real or apparent discrepancies of an order of magnitude, providing the incentive for focused big-science programs sponsored by the National Science Foundation (NSF), namely, PRPOOS (Planktonic Rate Processes of Oligotrophic Ocean Systems) and GOFs (Global Ocean Flux Study). The controversy is a healthy and exciting one that promises to remain heated into the 1990s, with several reasonable alternative hypotheses for the discrepancies being explored.

Optical technology is providing new observational resolution at both extremes of scale. Remote sensing of ocean color (Figure 6-1 in Oceanic Chemistry chapter) yields an entirely new view of regional and global biological oceanography, revealing such rapidly evolving patterns of plant standing stocks that the full impact of historical data bases of biomass and primary production has yet to be evaluated; it is clear, however, that shipborne measurement programs have been badly undersampled. At the opposite end of the spectrum

is flow cytometry, which is a method developed in medical science to arrange cells and other particles from samples into an orderly laminar flow, stimulate them with specific wavelengths of light, and measure a number of particle responses and characteristics (e.g., fluorescence at multiple wavelengths, forward and right-angle scattering, and Coulter volume)—each measurement clearly associated with a given cell or particle.

Flow cytometry is providing the first rapid assays of between-individual variability among phytoplankton (and among other microbiota). The importance of this level of resolution is difficult to overstate because it allows scientists, for the first time, both to invoke and to test strong biological theory. The most powerful ecological theories use optimization arguments that assume heritable variation among individuals and argue which individual characteristics will allow their bearers to leave the most successful progeny. Flow cytometry permits the testing of assumptions and predictions of such theory in both the laboratory and the field. One might draw the analogy in attempting to produce and test previous models to that of deducing natural selection and testing the idea with a knowledge of only the mean characteristics of individuals within populations. With flow cytometry one can, for example, examine the state of light adaptation of individual phytoplankters for comparison with models of their expected trajectories under varying mixing conditions.

Both the intellectual foment arising from questions of the magnitude of primary production and the results from these new technologies (among others) have led to a closer look at mechanisms controlling primary production. Since fluid motion controls access by phytoplankton to both nutrients and light, and since understanding of upper mixed-layer fluid dynamics has seen major advance in the last decade, the interaction of fluid motion with phytoplankton growth has received considerable theoretical, laboratory, and field attention. Gains from these interdisciplinary physical-biological approaches show no signs of abatement and cover size scales from the Kolmogorov scale (less than 1 cm dissipation scales), through the sizes of mesoscale eddies, and up to the general circulation of basins and oceans.

Microheterotrophs

An early candidate for the cause of the order-of-magnitude discrepancy in primary production rates was underestimation of primary production in carbon-14 incubations due to the activity of the "microbial loop" (Figure 4-1) in incubation containers. Most trophic steps span about one order of magnitude in body length (i.e., predators typically have 10^3 times more body volume than their prey). Discoveries over the last decade have revolutionized the view of material and energy flow below 10 micrometers, revealing that (1) submicrometer-sized cyanobacteria are often significant contributors to primary production; (2) only flagellates of order 10 micrometers in size are capable of making a living by feeding on bacteria (including the primary-producing bluegreens) and in turn that those flagellates closely regulate bacterial abundance to between 10^5 and 10^6 cells per milliliter; (3) rather than remineralizing, heterotrophic bacteria compete with primary producers for limited supplies of inorganic nitrogen; and (4) heterotrophic bacterial production typically uses between 30 and 50 percent of the total primary organic carbon production measured by ^{14}C . The first discovery was driven by new microscopic and filter technologies, the second by a simple but elegant scaling model, and the third and fourth by the advent of new isotopic techniques. The biggest remaining unknown is the mechanism whereby so much of the carbon fixed is shunted through bacteria; healthy marine phytoplankton have never convincingly been demonstrated to leak even as much as 10 percent of their net production.

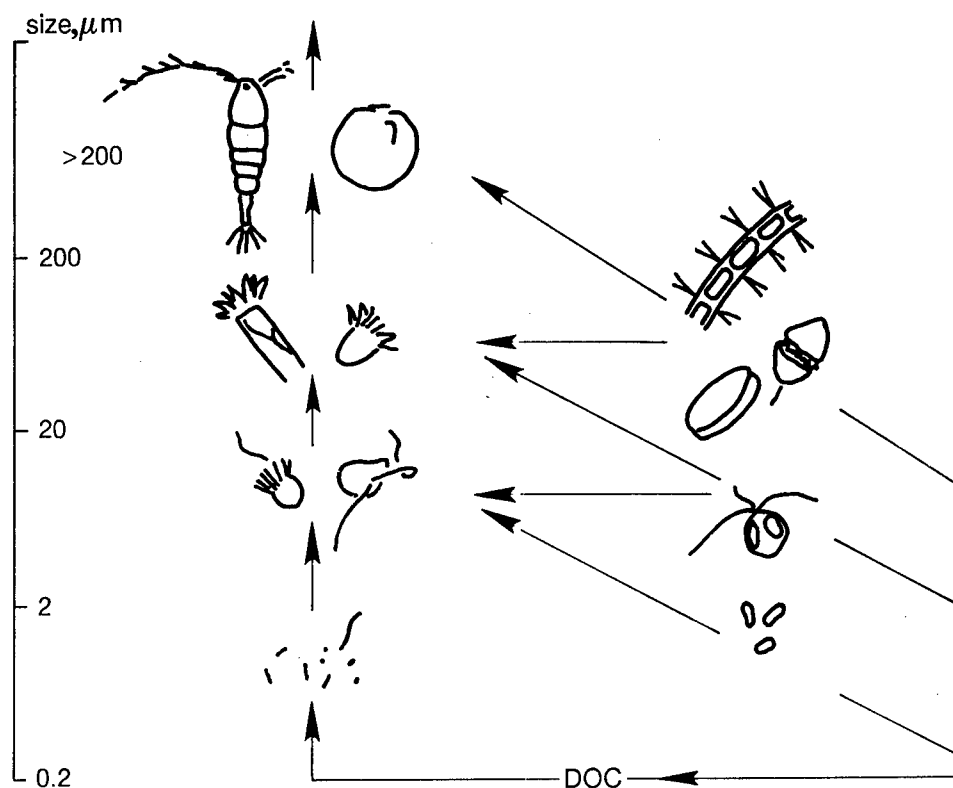


FIGURE 4-1 The "microbial loop" of a marine planktonic food chain (DOC = dissolved organic carbon) (Fenchel, 1987).

Heterotrophic bacteria and primary producers together play a key role as the only major sources of particles and sinks for solutes.

Changes in the chemistry of synthetic rubber manufacture caused sampling vessels that had been tested for toxicity—and found safe—to become toxic; this shift is now known to have been a major factor in the discrepancies among various primary production estimates, while focus on the microbial loop has led to conceptual advances of its own. Animals of sizes comparable with phytoplankton are now known to eat phytoplankton and cannot be readily excluded from incubations. Carbon fixed by plants, but then eaten and excreted by these micro- and nano-zooplankton, does not appear as primary production in the traditional analysis. Models suggest that these microheterotrophs (a heterotroph being an organism that obtains its organic carbon by other than primary production), whose doubling times virtually match those of their phytoplanktonic prey, will be particularly effective at controlling phytoplankton growth without major lags in predator-prey cycles. Models have yet to deal effectively with new findings that numerous chlorophyll-containing primary producers feed actively on bacteria and other particles of micrometer size.

The microbial loop, involving the flow of organic material among phytoplankton, microscopic (nano) zooplankton, and bacteria, has now been invoked to balance many ecosystem models of mass and energy flux. Few models will, in fact, balance without such a loop. Interactions among these microbes hold promise for replacing other explanations of the presence, timing, and absence of blooms, notably in the subarctic Pacific where the lack of blooms has previously been attributed to macrozooplankton grazing. (For a month or two in late summer, the system may be limited by insufficient iron.)

How fast the microbial loop spins and uses energy depends to a great extent upon the activity of bacteria, which are increasingly viewed as sinks for nutrients rather than as remineralizers. Especially where nitrogen sources are scarce, bacteria are increasingly viewed as competitors with phytoplankton for dissolved nitrogen compounds. In this view the nitrogen they lock up is not made available again until the bacteria are eaten and nitrogenous wastes are excreted by the bacterivore. A brilliant combination of biological scaling arguments and parameterization of the physics of the low Reynolds number flows in which 1 micrometer bacteria live and are hunted has shown that prey items of this size cannot be important as a food source for most planktonic animals greater than about 10 micrometers long. This analysis is now being seriously questioned for a few larger (100-micrometer) ciliates that apparently can subsist on bacteria, but apparent exceptions to date have proven to be special cases not covered by the general formulation. Even if the original analysis fails (which seems unlikely for the bulk of potential bacterivores), the focus it has given will have advanced biological oceanography dramatically. Recently developed methods for measuring bacterial growth rates typically show their carbon production to be 30 to 50 percent of the primary production measured by carbon-14 incubations. How bacteria acquire this large a fraction is perhaps the most serious question at present in our understanding of the microbial loop. Bacteriologists suggest that it comes from direct excretion or leaking of photosynthates from phytoplankton, but phytoplankton workers find no physiological or ecological evidence of such massive loss.

Optical technology and associated computer software—from flow cytometry, video imaging, and automated motion analysis to laser-Doppler velocimetry—have been instrumental in the rapid advancement of the understanding of encounter and capture mechanisms in zooplankton of all sizes. Chemical diffusion “shells” and minute pressure changes due to the presence of rigid particles in the flow have been shown to be used as cues for selective filtration of water parcels containing food; this view has replaced previous notions of indiscriminate, continuous, and energetically expensive filtration of large volumes of water.

Microenvironments

The study of spatial pattern or “patchiness” of organisms has been a traditional focus of biological oceanography, but concerns over chemical and pressure gradients of scales detectable by zooplankton exemplify the extent to which an appreciation of microenvironments has pervaded the field. Marine particle aggregates (“snow” as well as smaller aggregates) have been viewed as places where the microbial loop can spin faster because food is concentrated. Reduced gases have been shown to be produced by obligately anaerobic microorganisms (incapable of growing in the presence of oxygen) living in the well-oxygenated upper water column, which is possible only in the presence of anaerobic microenvironments.

With redox-specific dyes, reducing microenvironments too small even to be detected by microelectrodes are now being documented. New optical methods of viscosity measurement show biologically produced changes on the scale of surface microlayers and marine snow particles. Processes once viewed as homogeneously distributed (e.g., zooplankton excretion) are now viewed as point (or very local) processes. Distance from the source at the time of the event and intervening physical processes can confer an advantage or disadvantage, for example, in access to regenerated nutrients from zooplankton excretion.

This collection of findings has shattered the notion of the ocean as a homogeneous (in the sense of chemical reaction classification) fluid and replaced it with a picture of heterogeneous catalysis. It is necessary to treat biology, reaction rates, and diffusion rates in any mechanistic understanding of the coupling of biological and chemical oceanography.

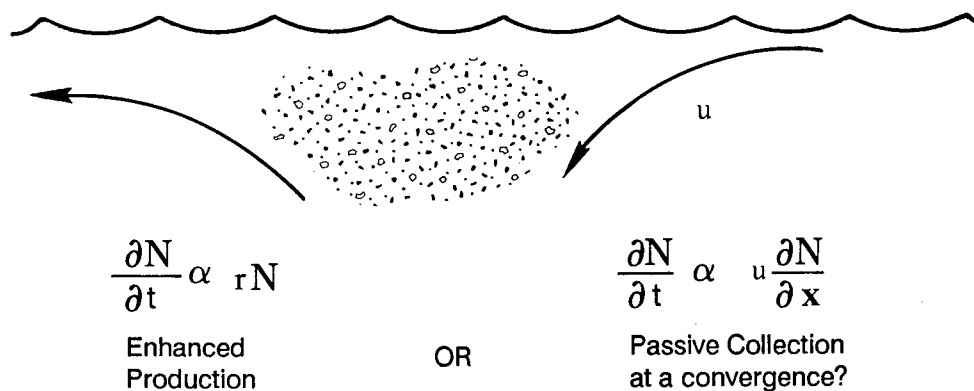


FIGURE 4-2 High plankton abundances at front.

In the water column on scales below the Kolmogorov scale of turbulence (order of 1 cm), these microenvironments are produced by the interaction of chemical diffusion, biological processes, and biogenic structure. In the sediments, where turbulence is nonexistent, diffusional gradients produced by organisms and their tube structures have been found to exert controlling influence over scales of tens of centimeters, affecting other organisms and controlling the magnitude and sometimes even the sign of chemical exchanges between the sediments and the overlying fluid.

On scales just above the Kolmogorov scale, the pervasive importance of fluid motions is becoming ever more widely appreciated. Fluid motion influences encounter rates of prey with predators both in the water column and at the bottom. Food supply to both suspension and deposit feeders on the bottom has been shown to be controlled by the details of flow and particle motion within the bottom-most centimeters of the benthic boundary layer. Theory and experiment are showing larval and bacterial settlement on hard and soft substrata to be dominated by fluid motion virtually until the moment of contact with the bed.

Mesoscale Variability

Appreciation for mesoscale heterogeneity is an equally dramatic change in the biological oceanographic gestalt, wrought in no small part by the rich tapestries of remote-sensing images that now adorn biological oceanographers' walls. It remains in many ways a frustrating change. Observed patterns are sufficiently complex and rapidly changing to thwart hopes held in the last decade of using patchiness as a simple inversion tool for understanding biological processes. Detailed studies of small numbers of individual rings (i.e., those in the Warm Core Rings Program) and fronts reveal a rich diversity of pattern that so far largely frustrates attempts at empirical or theoretical generalization. We know, for example, that fronts and rings are features across which primary productivity and zooplankton abundance show sharp gradients; we do not know the extent to which these changes are due to enhancement of production or to simple physical accumulation (caused by interaction of behavior and fluid convergence) (see Figure 4-2). Some progress is now being made by predicting and testing aggregate consequences of large numbers of rings transiting particular regions, such as predicting success of fish recruits.

It is easy in this challenge to overlook a very real advance. Prior to the acquisition of remote-sensing images, biological oceanographic measurements were strongly affected by what could only be regarded as stochastic variation. Placing oceanographic cruises in the

context of remote-sensing images allows reclassification of much of what would have been regarded as stochastic variability and, by allowing sampling designs stratified across features in space and time, dramatically improves the precision of estimates of both standing stocks and productivities. This reduction in confidence limits is an advance not only in empirical knowledge but also in the ability to resolve among predictions of competing models.

Long-Term Variability

It is somewhat more difficult to evaluate the status of investigations of large-scale, long-term biological variation. Statistical interpretations surely improve with increasing length of well-maintained time series, but evident improvements in understanding of interannual variations have been surprisingly rapid. Major changes in interpretation of year-to-year variability of biological phenomena, from primary productivity to year-class strength in commercially harvested fishes, are closely linked to rapid advances in physical understanding of long-term, large-scale oceanographic phenomena (such as progression of Kelvin waves across the Pacific as part of the El Niño syndrome or processes leading to year-to-year variations in bottom-water formation in the North Atlantic and driving other changes in the general circulation).

Phenomena once attributed to stochastic local changes (e.g., year-to-year variations in zooplankton standing stocks in the California current, thought to have been linked to stochastic changes in frequency of upwelling-favorable winds) have been shown instead to be more closely linked to far more predictable changes in pattern and strength of the general circulation. Biological oceanographic assimilation of advances made in general circulation modeling has been reasonably straightforward and noncontroversial because the scales involved do not allow much in the way of strong interactions with biotic systems; i.e., it is fairly safe to assume that the physical process drives the biological response and that the coupling is more or less linear.

Unusual Environments

How little explored the deep ocean has been biologically is continually impressed upon biologists by the ongoing recovery of unnamed life forms. The recent discovery of communities near hydrothermal vents, entirely unknown previously, is emphatic confirmation for the layperson. The discovery of highly thermophilic bacteria at the base of the food webs of hydrothermal vents has raised issues in xenobiology, the origin of life on earth, and thermal acceleration of biotechnological production. Studies in these extreme environments have led to much better understanding of biological processes in widespread environments such as the redox discontinuity found at a few centimeters depth in shallow-water sediments.

Biological systems often defy scaling down for laboratory experimentation because organism size is more or less fixed and the physics of the processes cannot be scaled down or up without resort to unnatural temperatures or fluids inimical to life. Thus biologists must continue to resort to "natural experiments" in the sense of making predictions concerning what would happen under a particular combination of biological and environmental conditions and then seeking those conditions. Communities newly discovered at cold seeps (of chemically reduced substances from the seafloor) and those being more fully explored in the dynamically and geologically complex environments of seamounts, in eddies of various sorts, and in extremes of tropical and polar environments are being used increasingly in this valuable hypothesis-testing mode.

NAVAL RELEVANCE

Progress in biological oceanography can have a strong though indirect impact on naval missions. The ocean's biomass is composed primarily of microscopic planktonic organisms, which interact intimately with oceanic chemistry by taking in nutrients and excreting waste, and in death by their ultimate dissolution. Plankton are ubiquitous in the ocean, though their absolute numbers and population structure vary by orders of magnitude temporally and spatially. Their ubiquity is responsible for inevitable fouling of ship hulls and saltwater piping, and destruction of piers worldwide. Economical yet environmentally safe control or elimination of these effects would lead to enormous savings in fuel and maintenance costs.

Organisms living freely in the ocean also affect naval operations. Acoustic energy is absorbed and scattered by plankton, particularly at the higher frequencies employed by torpedoes and by mine-avoidance sonars. Nekton may emit sound as well as attenuate it, so that organisms can degrade the performance of both active and passive sonars. Like biofouling, this topic is of continuing, major Navy interest. Organisms may also scatter or emit light. Biologically rich water frequently has a short optical attenuation length; the phenomenon of bioluminescence is well known to highlight the wakes of ships. The effectiveness of optical search and communication systems, be they remote or in situ, depends directly on these biological features. A knowledge of their bio-optical characteristics, temporal and spatial variability, and dynamics is required to support system design and performance estimation.

Most of the biomass drifts passively with ocean currents, so remotely sensed differences in optical properties can be used to distinguish water masses. Coupled with predictive models of population dynamics, this fact may permit estimates of the boundaries, velocities, and acoustic and optical properties of specific water masses. Continued research will be required to discover the extent to which such estimates are limited by stochastic variables.

Although planktonic organisms exert the most persuasive and important influence on naval operations, because of their ubiquity, a continuing need exists for fundamental knowledge to support both intentional and accidental naval interaction with larger nekton. Sea lions, whales, and porpoises have all been effectively employed in naval work situations; their communication techniques and swimming kinetics have been studied to support acoustic and ship design. Cables suffer from shark and fish bites; navy swimmers, divers, and downed pilots, are exposed to sharks, sea snakes, jellyfish, and other biological hazards; benthic organisms modify the bottom and influence structural stability and reflection characteristics. Not merely by virtue of its dominant presence in many coastal, port, and harbor environments does the Navy have a vested interest in environmental quality and thus in research to understand the influence of its personnel and machines on the ocean and nearshore biomass. The Navy has been a leading supporter of research in these areas in the past; while many fundamental questions have been answered and interest has properly shifted primarily to the civilian sector, enough issues of relevance to the Navy remain that such areas cannot be ignored.

Finally, there are materials present in the ocean that are obviously organic, but about which virtually nothing is known. For example, marine snow is the name given to delicate aggregates of flocculent material that have been observed in the ocean. Marine snow could provide a valuable tool for studying the time history of ocean turbulence, and thus potentially for wake discrimination, if we can describe its life cycle and physical properties with some degree of confidence. So-called organic films are also of naval interest, primarily for their postulated effects on the emission and backscatter of visible and microwave energy from the ocean surface. They are believed responsible for documented observations from

space of ships' wakes tens of kilometers in length as revealed in the glitter pattern. The constituents of organic films may be present throughout the ocean, but little is known about their sources or sinks, or the physical properties of their constituents.

CURRENT PROGRAM

The overall objective of the Oceanic Biology Program is to understand Navy-relevant biological processes in the marine environment under a variety of scientific topic areas or involving a number of phenomena such as luminescence, acoustics, deterioration, and sensory perception.

The program is divided into four major areas of research:

1. **Biological Oceanographic Processes.** The largest area in the program, it examines the processes leading to the observed distribution of key biological elements. It addresses biological phenomena that play a part in signal-to-noise problems encountered by Navy active and passive sensor systems.
2. **Marine Biodeterioration.** This area develops quantitative information on the biological and chemical processes in natural marine systems that initiate, and control rates of, biodeterioration of materials introduced into the sea.
3. **Biological Particle Dynamics.** This area focuses on those biological processes affecting particle distributions and their properties (geophysical, optical, etc.). It concerns both particles in the upper and midwaters of the ocean as well as those near the bottom, such as sedimentary particles.
4. **Advanced Technology to Study Oceanic Biological Processes.** This research area is clearly fundamental to the future development of the study of the biology of the sea. The first objective is to understand how organisms sense their environment and modulate and process the signals in the environment. Another objective is to utilize the newest and most appropriate acoustic, optical, computer, and biomedical technologies to solve the problem of real-time sampling in biological oceanography.

In all of the research areas, the importance of modeling is being emphasized because of the role that models can play in focusing research efforts. This focus is especially crucial in oceanographic modeling dealing with the prediction of physical-biological interactions because of the expense of unfocused oceanographic field research.

PROMISING RESEARCH TOPICS

Bio-Optics

A promising area that new optical models, new upper mixed-layer physical models, and new optical technology (both in water and out) make ripe for investigation is the interrelationship among fluid dynamic, optical, and biological patterns and processes. This subfield is known as bio-optics. The issues are complex and highly interdisciplinary. Upper-ocean mixed-layer dynamics, phytoplankton growth, and light fields interact strongly and nonlinearly.

The shortage of available talent in marine optics at U.S. academic institutions appears to be limiting the rate of progress to some extent. Marine optics is taught at few institutions, and few of the existing experts are training graduate students. Identifiable sources of funding for research in marine optics are few and small, promulgating a closed-shop mentality among practitioners and stunting growth of this area. There is a definite need for more optical

oceanographers or more biological oceanographers with solid training in optics to deal with the important and very basic questions raised but not yet answered. For example, what organisms are responsible for most of the light scattering in the open ocean?

ONR programs (ODEX, BIOWATT) have generated a good appreciation for optical variability and some of its causes in a few particular areas. There is a distinct need for broader geographic understanding, not to mention the still daunting problems of working closer to shore where suspended inorganic material and complex physical circulation compound the difficulty of predicting optical characteristics.

ONR has a clear niche to fill. The National Aeronautics and Space Administration programs focus on remotely sensed variables, while the recent NSF focus is on the global scale. A process-oriented focus by ONR on in-water optical properties is essential to fill the Navy need and necessary scientifically to understand causal mechanisms.

Plankton Distributions and Their Relation to Fluid Dynamics

Similarly at the micro- and meso-scales, ONR has an opportunity to take a stronger lead in the study of biological-physical coupling. Some of the problems under this umbrella are subsets of the issues addressed in BIOWATT, but others clearly are not. In the latter category are issues of the role of passive transport in larval and bacterial recruitment, in the accumulation of organisms at fronts, and in the production of patterns of organism succession. To date it remains productive to ask how well passive processes (e.g., drifting with the net current or sinking) can explain organism distributions, but the need is growing to incorporate organism motility, behavioral response, and population growth explicitly in predictions and measurements finding departures from these sorts of null models. Most biological processes occur inherently at the micro- or meso-scale, and thus it is propitious that the ONR physical oceanographic effort has specialized on this end of the spectrum. Even so, many of the physics issues seem more related to fluid dynamics than to physical oceanography.

Many of the issues here concern the ability to measure biological parameters with the same spatial and temporal resolution as those of physical processes affecting their evolution. Thus the need continues and intensifies for rapid (e.g., acoustic or optical) measurement techniques deployed from ships and for reliable long-term, moored instrumentation for biological measurements. An example of a success here is the simultaneous collection of bio-optical and physical time series from the BIOWATT mooring, and the continuing need for development is seen in the evolving Coastal Transition Zone ARI. Similar coherence analyses are beginning between physical and bioacoustical measurements.

As an example of a potential future issue, ONR is well poised to attack the issue of particle aggregate dynamics in the ocean. Since particle aggregates scatter less light than would their homogeneously dispersed component particles, the issue is an important one for bio-optics as well.

Particle aggregation depends on physical processes (e.g., shear, which can either cause particles to collide or rip them apart) as well as biological and chemical ones. Many of the requisite measurement and modeling techniques can be borrowed from sediment dynamics programs in which ONR has played a major role. Instrumentation again is an issue, as is the bringing together of the requisite expertise. Physical oceanographers concerned with microstructure, for example, do not usually get training in the physics of fluid-particle mixtures. Conversely, biological oceanographers rarely obtain a strong background in small-scale fluid dynamics, so creative management and education is required to bring the necessary pieces together. While it might be argued that processes of particle aggregation

will be well measured by programs such as GOFs, the evolving approach of GOFs appears to be more empirically aimed at flux measurement rather than mechanistically aimed at flux prediction.

Biological Oceanographic Modeling

In part because of the perceived failure of community- and ecosystem-level theories to make hoped for and (sometimes promised) substantial advances in understanding within general ecology, and in part because of misguided attempts to incorporate ill-tailored and hopelessly complex mathematical models into biological oceanography, there is a dangerous tendency among biological oceanographers to downgrade the role of theory. Its importance in an environmental science where observations are difficult to collect cannot be overemphasized. Without a theory specifying what needs to be measured and how well, observational effort is doomed by measurement redundancy or by the failure to make simultaneous measurements of variables later discovered to be related and important.

How to define and catalyze good biological oceanographic theory is difficult to suggest, but it is possible to pinpoint some failures and analyze the reasons for them. Conversely, some major successes can be identified. Numerous efforts to bring good applied mathematicians into the effort to solve ecological modeling problems have led to disillusionment because of initial failure to pose the important ecological question clearly before applying sophisticated modeling approaches. Arguments by analogy or gross borrowing of theories from other disciplines typically have failed as well. Information theory ultimately has brought little to the understanding of communities; systems analysis has failed to provide sufficient boundary conditions for closure of biological systems questions; statistical mechanics has brought no insight into biological oceanography despite repeated attempts. Analogy does not guarantee homology, and none of these approaches has incorporated strong biological constraints. Perhaps the most successful body of ecological theory is foraging theory, which has flourished over the past 20 years precisely because it incorporates strong biological constraints of fitness and continues to make testable predictions concerning ecologically important and measurable variables.

The most successful models within biological oceanography are those concerning physical mixing of phytoplankton within the marine light field. The strong biological constraint is the same one formalized by foraging theory: the organism that fails to gain enough energy to balance its metabolic losses fails to reproduce. These modeling approaches have been interdisciplinary from the outset and have not used mathematics beyond the capabilities of ordinary biological and physical oceanographers. They seem to form a good jumping-off point for dealing with more complex problems like those of predicting oceanic light transmission.

New technologies allowing new measurement resolution should help drive and can certainly help to justify new modeling efforts. Predictions of inter-individual variations in light-absorbing abilities were not very useful before the flow cytometer was introduced, since there was no ready way to test them. Satellite images tempt one to make synoptic predictions for large areas. It is arguable that biological oceanography would be a much healthier discipline if models were more clearly driving new measurement schemes and technologies rather than being used predominantly to assimilate empirical data into a more compact, interesting, and generalizable form, although the importance of the latter use of models should not be minimized.

Modeling is itself a good catalyst for intellectual interest from a broader audience. If someone can get excited, either positively or negatively, about a prediction, he or she is

much more likely to make measurements of the predicted variables than if no theory had been formulated. As an example, while the ONR Oceanic Biology Program has been highly successful in developing acoustic tools for measuring zooplankton abundance, it has not been especially successful in enticing non-ONR investigators to be interested in using them. Theory about what alternative patterns might be expected of zooplankton would greatly pique interests in such measurement programs.

Even the suggestion of such modeling catalyzes the posing of new and interesting questions. We know that organisms are not purely passive particles. Thinking about how to incorporate behavior in models of particle motion through a fluid immediately generates questions as to the ability (distances and thresholds) of organisms to sense fluid dynamic stimuli and signals from one another. Relevance to naval signal and noise problems is virtually immediate.

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5

ARCTIC SCIENCES

Arctic oceanography encompasses the study of the mostly ice-covered Arctic Ocean and its seasonally ice-covered peripheral seas, including the Bering and Greenland seas and the shallow seas north of North America and Eurasia (Figure 5-1). It aims to understand and predict the distribution of ocean and ice properties, their circulations and transformations, and their interactions with the atmosphere and the rest of the global ocean.

TRENDS AND RECENT PROGRESS

Arctic oceanography is of fundamental scientific importance for several reasons. The Arctic Ocean and its peripheral seas affect the earth's climate system in two major ways. First, they are a major source of deep water for the global ocean and thus a major site for the interaction of the atmosphere and ocean. Second, Arctic ice cover is a major influence on the albedo of the earth and thus the total amount of heat that the earth absorbs from the sun. Many of the oceanographic processes that occur in the Arctic also occur in other oceans. The stable platform provided by the ice cover, however, often makes the Arctic an ideal location for their study. In addition, the ice cover acts to attenuate the effect of atmospheric forcing on the ocean, thus facilitating the study of oceanic processes not immediately related to atmospheric forcing.

Arctic oceanography has traditionally been isolated from the mainstream of oceanography with many practitioners identifying themselves more with the broad field of Arctic science. Even today many Arctic oceanographers do no work outside of the area. The trend in recent years has been toward more interchange between Arctic oceanography and the rest of the field, to the benefit of both.

Ice

The major difference between polar oceans and the rest of the global ocean is the presence of sea ice. Ice is a factor operationally, and in the behavior of the underlying ocean. The Arctic ice cover is not of uniform thickness. It is rather a collage of ice pieces varying in thickness and size with open or thinly iced leads and ridges of thick ice between floes. Models are needed to predict the motion of the ice, its thickness, and the likelihood

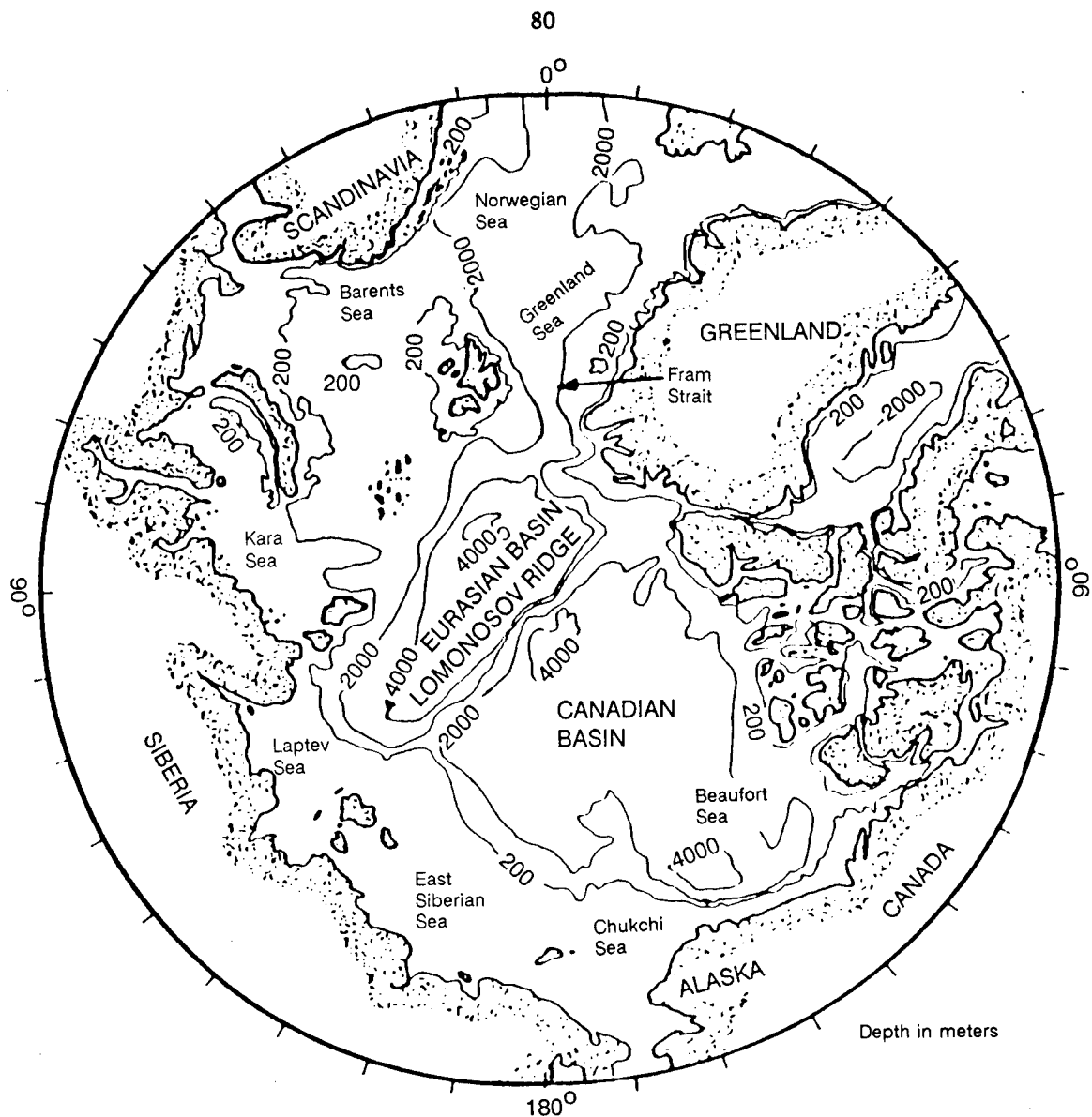


FIGURE 5-1 The Arctic Ocean and its seas.

of leads and ridges in a given area. Current models, based on observational studies made during the 1970s, produce good estimates of ice motion but have less skill in estimating mean ice thickness and ice edge. Their effectiveness in predicting ridges and leads is unknown because of inadequate data for model verification.

The greatest deficiency in our current understanding, and thus in current models, is concentrated in two areas. First, the flux of heat from the ocean into the ice cannot be adequately assessed. Ice thickness, however, is quite sensitive to this quantity, particularly in the marginal ice zone (MIZ) where fluxes can be large. Second, only a few measurements are available from the distribution of ridges, leads, and floe thicknesses, and without such measurements it is difficult to understand or model these properties of the ice.

Observationally, recent progress in measuring the Arctic ice has been made by the Arctic Buoy Program, which now routinely maps the large-scale fields of surface pressure

and ice motion in the Central Arctic, using autonomous satellite-tracked buoys placed on the ice. Passive microwave remote-sensing techniques are capable of discriminating between water and ice over the entire Arctic on a nearly routine basis, independent of daylight and weather.

In the MIZ, intensive studies in both the Bering Sea and the Greenland Sea have made significant progress in describing these areas. In the Bering Sea, where the oceanography is not complex, relatively simple ice models have been successful in predicting the advance of the ice edge on a weekly time scale. The more complex oceanography of the Greenland Sea has made this task more difficult.

Arctic Ocean Circulation

The basis of all oceanographic studies in the Arctic is a description of the large-scale circulation patterns and the distribution of temperature, salinity, and other oceanographic quantities. In broad terms, the Arctic can be divided into several regimes: the mostly ice-covered, Central Arctic; the seasonally ice-covered coastal regions; and the seasonally ice-covered marginal seas. In recent years considerable new data have been collected in the non-Soviet coastal regions and marginal seas, using the combination of icebreaker, aircraft, and moored and drifting buoy measurements. These efforts are producing a good descriptive base, but in the Central Arctic, particularly the Soviet sector, logistical problems have inhibited data collection (Figure 5-2). Our knowledge of this area is fragmentary and insufficient to test models of ocean circulation. Progress has been minimal since the 1970s, and the classic papers in the field date from that time.

Water Mass Formation

The past few years have seen an increased understanding of the role of the Arctic Ocean and its peripheral seas in the circulation of the global ocean. The Greenland and Iceland Seas appear to be a major site for the transformation of warm surface waters into cold deep waters, which subsequently spread into the entire global ocean. This process exchanges water between the surface layers and deep ocean, greatly increasing the ability of the ocean to buffer changes in atmospheric composition, man-made or otherwise. The details of this process are not understood, and its quantification is a priority in climate research.

Recent studies, primarily those using high-quality hydrographic and man-made tracer measurements, indicate that the Greenland and Norwegian seas and the Arctic Ocean are all important in the eventual formation of deep waters in the Greenland Sea (Figure 5-3). The basins interact through a series of strong boundary currents, such as the one that flows eastward along the slope north of the Barents and Kara seas. In the Arctic Ocean itself, the production of cold salty water on the shallow shelves during ice formation and its subsequent exchange with water in the deep basin appear to be key processes in determining the water properties.

Mesoscale Structures

Mesoscale processes are intermediate in size between the large-scale circulation of the Arctic and the smaller scale processes more directly involved in mixing. In the Arctic this includes scales ranging from kilometers to hundreds of kilometers. Eddies and the meandering and pulsation of currents are typical manifestations of mesoscale activity. These manifestations are often the major factors in determining the local oceanographic

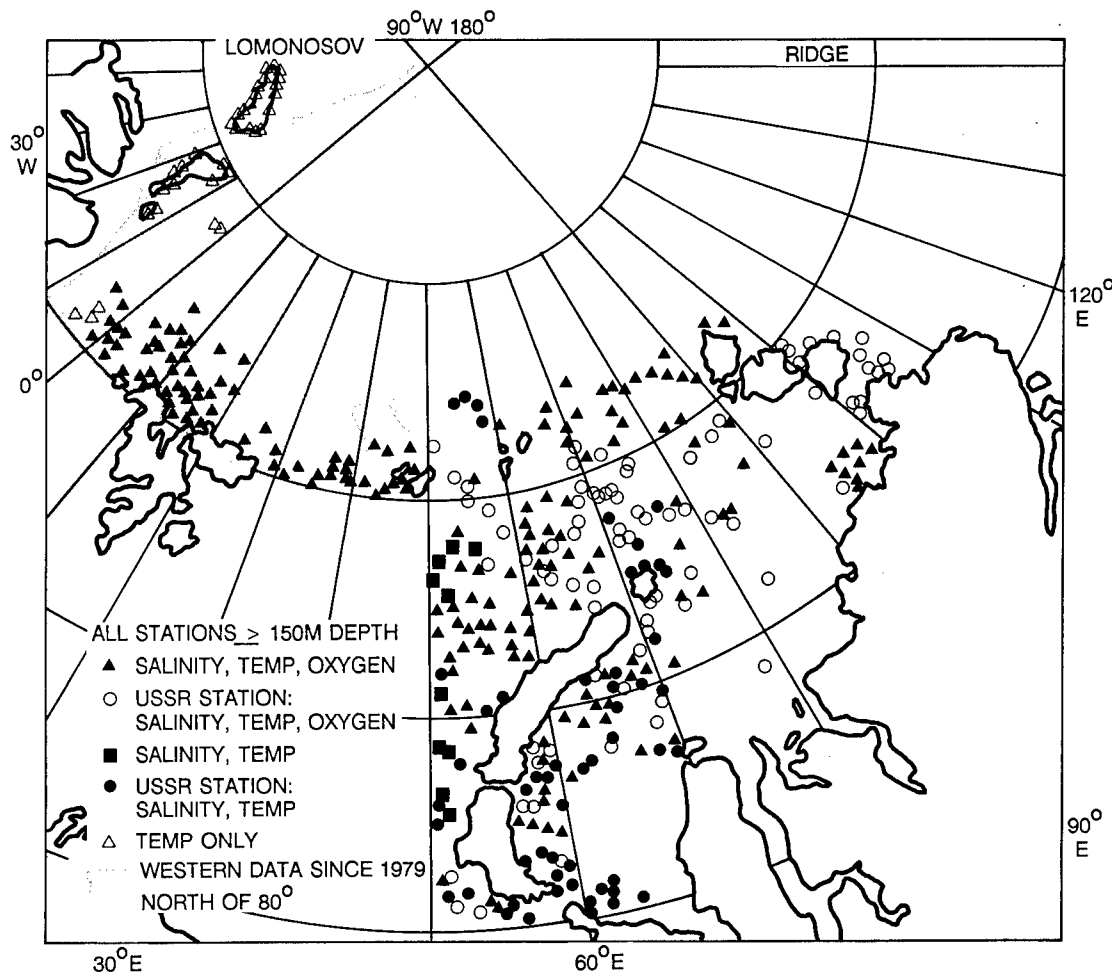


FIGURE 5-2 Available hydrographic data in the eastern Arctic Ocean on file with the World Hydrographic Data Center, updated by regions of western data since 1979 (shading).

environment both for smaller scale processes and for operational purposes. Although improving, our knowledge of Arctic mesoscale processes is still fragmentary, particularly in the Central Arctic.

Most recent Arctic mesoscale measurements have been at the ice edge in the Greenland Sea. This is a complex region with strong mesoscale fronts and eddies. Despite intensive effort only a descriptive picture of the mesoscale activity has emerged so far. In the Central Arctic the existing data suggest that mesoscale activity is weak, with the exception of a large number of strong isolated circular eddies in the Beaufort Sea. The existence and characteristics of these features are well documented, but their origins and lifetime are only poorly known. The extremely limited data suggest that they are less common in the Eastern Arctic. Undiscovered fronts and regions of eddy activity quite likely exist in the Central Arctic. Its overall importance in oceanic or ice dynamics has yet to be determined.

Internal Waves and Microstructure

These smallest oceanic scales are important both to acoustic propagation and in determining the vertical fluxes of heat, salt, and nutrients. They are particularly important

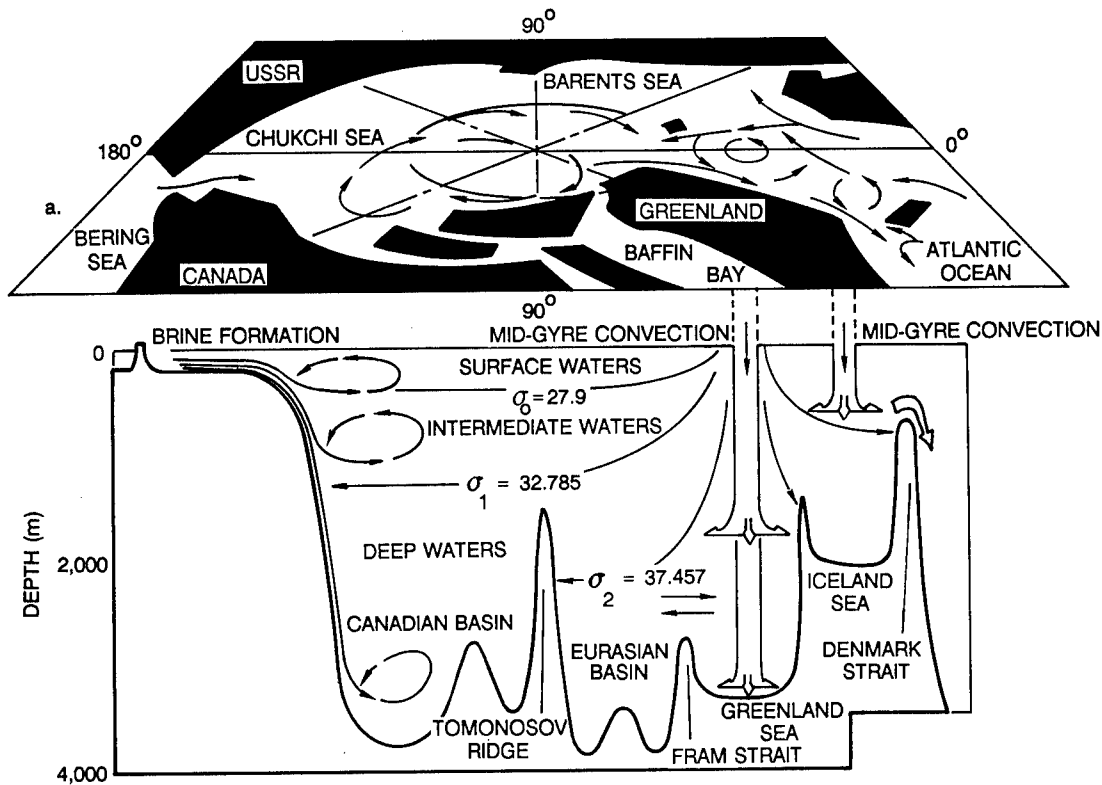


FIGURE 5-3 Schematic of deep water formation in the Arctic. Major surface circulation features (upper panel) are the Bering Sea inflow (a), the Beaufort Gyre (b), the transpolar drift (c), the East Greenland Current (d), the Norwegian Atlantic Current (e), the West Spitsbergen Current (f), the Greenland Gyre (g) and the Iceland Gyre (h). Associated deep circulations (lower panel) in a vertical section along the 0 to 180 meridians show open-ocean deep convection occurring only in the Greenland and Iceland gyres and reaching the bottom only in the Greenland Gyre. Near-boundary convection along the edges of the Arctic Ocean renews water masses down to the bottom of the basin. (Aagaard, et al., 1985)

in the Arctic where upward heat flux from the ocean is known to play a major role in determining the thickness of the ice (Figure 5-4). Furthermore, the Arctic offers a special opportunity for small-scale ocean studies, both because of the lack of surface waves and direct wind forcing, and because of the stable platform provided by the ice, which will easily allow simultaneous, spatially separated measurements to be made.

Arctic Biology

Oceanic biology in the Arctic contains most of the elements of mid- and low-latitude oceanic biology, but some particular items are especially important, and a few special aspects are only present in the Arctic.

For example, high primary production is found in summers along marginal ice zones; since these are also regions of ventilation of the deep ocean, and of deep-water formation, these zones may be vital for long-term or even permanent carbon sequestering. Thus, increased description and understanding of the primary production and its physical and chemical controls are essential everywhere, but are especially relevant in the Arctic. In a complementary way, the interpretation of remotely sensed data as an aid to biological inference is especially important in the logistically difficult Arctic.

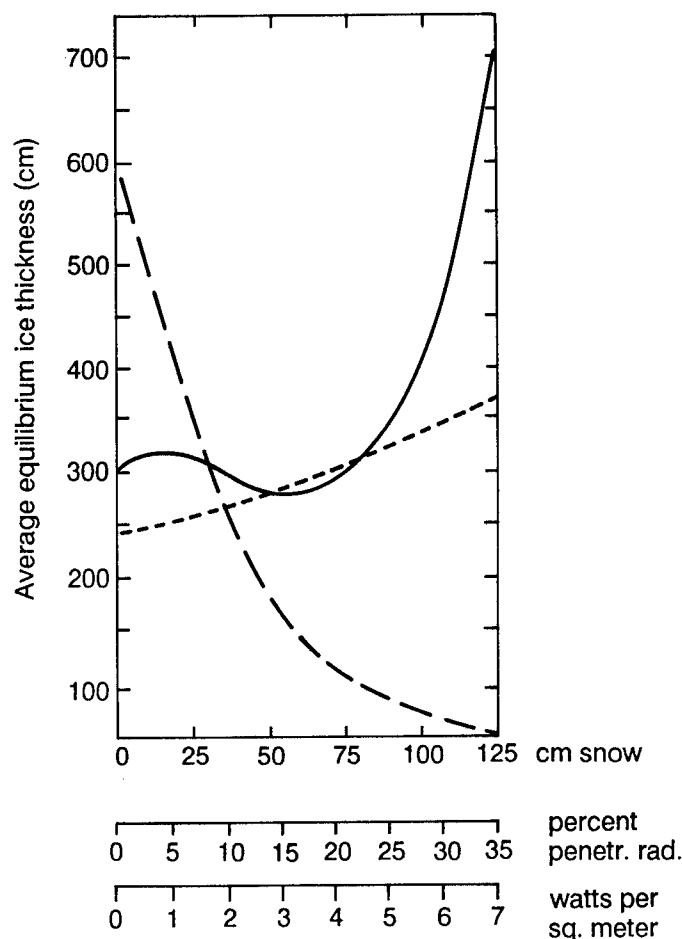


FIGURE 5-4 Annual average of the equilibrium ice thickness as a function of snow cover (solid curve), percentage of incoming solar radiation penetrating the surface (dotted curve), and heat flux from the ocean (dashed curve). External forcing functions were chosen to represent the present climate of the central Arctic.

It is not clear whether conventional wisdom about the relative importance of micro- and macro-organisms in biological hot spots is applicable in the Arctic. Although many of these issues are closely related to the MIZ (i.e., simply because the MIZ is the part of the Arctic about which something is known of the biology), almost any data and surely any unifying concepts about the biology of the Central Arctic would be welcome.

The kinds of issues being studied in the Arctic regions—mostly in the MIZ and in the Greenland Sea—are sedimentation and particle (vertical) recycling and redistribution, phyto- and zoo-plankton distribution and growth during the winter-to-spring transition, and biophysical modeling based on an ice-air-ocean physical model. The following topical areas most need increased research:

- primary production and nutrient interactions, including biogenic particle fluxes;
- food web and transfer relationships, on a seasonal basis;
- role of higher trophic-level organisms in polar marine ecosystems;
- remote-sensing indicators of biological processes, especially ocean color (conversion algorithms to give chlorophyll in polar waters are urgently needed); and

- benthic processes and material fluxes to the bottom, especially carbon cycling and its role in the global carbon budget.

NAVAL RELEVANCE

Arctic research is the primary geographically oriented program of the U.S. Navy. The Navy's maritime strategy, the maritime component of our national strategy, is designed to enhance deterrence and, should deterrence fail, contribute to forward defense and alliance solidarity. All of these dictate U.S. Navy operations in the far north, extending into the Arctic.

One Navy contribution to enhancing deterrence, as envisioned by the maritime strategy, is making it clear in peacetime and by crisis and wartime operations, that Soviet nuclear-missile carrying submarines (SSBNs) will be at risk in a conventional war. Soviet SSBNs are held near the USSR in defensive bastions protected by the bulk of Soviet naval general-purpose forces, especially nuclear submarines (SSNs). To carry out this role during peace, crisis, and war, the Navy must have and must demonstrate the capability for effective ASW operations in northern latitudes and extending into the Arctic to wherever the Soviet Navy may choose to deploy its SSBNs.

In wartime both forward defense and alliance solidarity require sea control in far northern waters to permit U.S. Naval and Marine Corps forces to assist in the defense of our allies, e.g., Norway and Japan. Our forces must also be able to prevent the Soviet Navy from deploying outward to threaten allied shipping lanes. These warfighting goals will best be accomplished by destroying the Soviet Navy—especially its submarines—through our conduct of offensive operations, especially ASW, in Soviet home waters, including the Arctic.

Our Navy's interest in the Arctic, therefore, has focused on submarine operations and ASW to counter the Soviets. The needs in these operational areas are quite broad and have mandated research into virtually all aspects of Arctic oceanography, including ice characteristics, motion and roughness, acoustic propagation, turbulence, optical characteristics, and bottom morphology. Basically, most physical, chemical, biological, and geological ocean parameters are as relevant in the Arctic as they are in the open ocean, with the added interest of the influence of the ice itself.

In addition to the traditional needs described above is the well-recognized and continuing demand for high-quality information on ice location and characteristics for ship routing, as well as for rescue. Also emerging are naval requirements, as well as new operational capabilities, that will strongly influence the nature of future arctic research. First, the advent of routine, remote ocean sensing offers the new possibility of detailed and continuous coverage; it is essential to learn how to interpret the resulting data to describe arctic characteristics such as ice depth, age, and motion. Second, the probability of increased duration and frequency of arctic operations implies a need for even more detailed and continuous spatial and temporal coverage. Third, the likelihood of critical on- and above-ice operations implies expanded requirements for knowledge of, and an ability to predict, arctic meteorological conditions.

While the Navy's operational interest in the Arctic has waxed and waned over the years, ONR has continued to recognize that the unique environmental characteristics of the Arctic must be understood if we are to successfully operate near and under the ice. ONR historically has been a primary source of continuity in U.S. arctic research through the years of operational neglect and thus has provided a strong base for the periodic surges of operational attention. This continuity is commendable and essential.

At the same time, the panel notes that current and anticipated operational needs demand that arctic science be brought into the mainstream of oceanographic research. U.S. arctic research has gone beyond its early exploratory phase and can no longer be conducted solely by small groups of arctic specialists. Rather, specialists and experts from other topical areas of oceanography must apply their expertise to problems of arctic interest, if the subtle and difficult issues that affect the operations of modern naval systems and remote-sensing instrumentation are to be properly addressed.

CURRENT PROGRAMS

The scientific objectives of the arctic program are to determine the temporal and spatial structure of mass, momentum, and energy fields within the arctic system; to understand the order and mechanism of interaction among principal structural components; and to determine the net flux of principal system constituents. Mass includes both inorganic and organic elements, for example, the water itself (solid and liquid phase), dissolved ionic species, biomass over several trophic levels, and derived suspended material. Momentum and energy include a spectrum of motion from acoustic vibrations to large-scale planetary waves.

Arctic research at ONR has been a geographically oriented program. This is appropriate because of the greatly different logistical needs of research on an ice-covered ocean. The program is organized into three core elements: (1) modeling systems, (2) sensor systems, and (3) infrastructure systems. Basic arctic research is pursued continuously within each core program. In addition, all core programs contribute to defined regional studies of finite duration. The modeling systems element comprises (in order of priority) dynamics, meteorology, geological oceanography, geophysics, and chemical oceanography. The sensor systems element comprises (also in priority order) electromagnetic remote sensors, acoustic remote sensors, and optical in situ sensors. Infrastructure systems comprise (in order) platforms, data management, and technical personnel. Current regional studies are focused on the Fram Strait and Northern Greenland seas, the MIZ, and to a lesser extent the Bering and Chukchi seas.

The current ARIs include arctic acoustics, real-time environmental arctic monitoring (R-TEAM), and arctic oceanography.

Arctic Acoustics

Research in this ARI supports basic research in theoretical and experimental underwater arctic acoustics in three areas of interest to the Navy: (1) high-frequency scattering from the under-ice surface and from the MIZ small-scale temperature features, (2) ambient noise research at low and intermediate frequencies, and (3) acoustic tomography to infer water-mass properties and, potentially, under-ice reflectivity.

Real-Time Environmental Arctic Monitoring

Programs in this ARI, R-TEAM, support development of under-ice, moored, environmental arrays with the capability of data transmission in near-real time.

Arctic Oceanography

The following are the research objectives in this field:

- Determine the processes that force the vertical and horizontal transport of water in the Arctic.
- Determine the mechanisms that couple the diverse, fine, and microscale processes to the mesoscale. This and the preceding objective include the continuation of the study of Arctic internal wave and microstructure.
- Determine the coupling mechanisms between bio-optical and bio-acoustic processes and physical processes.
- Assess the role of eddies in vertical mixing and in subsequent biomass blooms.
- Understand how the atmospheric-planetary boundary layer evolves from stable and shallow over ice to deep and mixed over water, and the consequent effect on oceanic dynamics.

PROMISING RESEARCH AREAS

Arctic Drifting Buoys

Few measurements can be made in most of the Arctic Ocean, particularly the Central Arctic and the Soviet sector (Figure 5-1). In the near future, it seems unlikely that such fundamental data will be collected by any means other than drifting buoys.

This is a technical area of great promise for arctic oceanography and a possible area for future accelerated research. A multiyear program of float and buoy deployment would vastly increase the amount of basic oceanographic data on the Arctic. The result would be an "Arctic Atlas" of velocity, temperature, and salinity profiles, as well as more complex quantities, such as internal-wave and mesoscale energy levels and the location of fronts. It is likely that this would become the basic reference for arctic oceanography in future years. It would allow current Arctic Ocean models to be tested and new ones to be developed.

The combination of remote-sensing, satellite-tracked drifting buoys, and deep-drifting sound fixing and ranging (SOFAR) floats offer the possibility of gathering high-quality data throughout the Arctic Ocean at a reasonable cost. Initial models of several types of buoys have been built and deployed in recent years. They are tracked by and relay their data via satellite. Ice buoys are capable of measuring the mass balance of an ice floe, and thus permit calculations of the ice thickness and flux of heat from the ocean. Oceanographic buoys are capable of measuring temperature and salinity in the upper few hundred meters of the ocean. Other variants under development should be capable of measuring upper-ocean velocity and tracking deep-drifting SOFAR floats to measure the deep velocity. Lifetimes of several years are possible, which should allow buoys to drift throughout the Arctic, including the Soviet sector.

A relatively small number of buoys and floats, deployed over a number of years, would vastly increase the amount of oceanographic data in the Arctic. These data would allow the testing of arctic circulation models and the verification of remote-sensing techniques. The result would be a greatly improved picture of the Arctic circulation, and the geographical levels of mesoscale activity, internal waves, and small-scale variability.

Currently, work on arctic drifting buoys is supported primarily by the Naval Oceanographic Office and oriented toward data gathering in support of the fleet. A research-oriented program using this technology should be started.

Ice Thickness and Deformation

Current models of ice dynamics link ice thickness, deformation, and thermodynamics. Ice thins by melting or breaking apart; it thickens when it is cooled or pushed together. Until recently, these models could not be verified because of the lack of adequate measurements, particularly of deformation. These can now be made using sequences of synthetic aperture radar (SAR) images, which will be available from the European satellite ERS-1, and potentially from Japan's JERS-1 and Canada's RADARSAT. Ice thickness and the presence of leads and ridges can now be measured using upward-looking sonars moored to the bottom or mounted on submarines, either manned or remotely piloted. The combination of these techniques is promising for future accelerated research and should allow considerable progress to be made in understanding and modeling the properties of ice.

Deep-Water Formation

Deep-water formation in the Greenland Sea is an arctic process of fundamental importance to the circulation of the world's oceans. A large-scale, coordinated international program, the Greenland Sea Project, will make intensive observations of the events surrounding deep-water formation for 5 years beginning in 1987. Conceived primarily by U.S. scientists, the Greenland Sea Project is being carried out mainly by Europeans. For example, studies of the ice budget were intended to be a major U.S. contribution but are not being taken. Other U.S. contributions, including process studies, may also benefit from the combined efforts of the other participants. A small number of high-quality hydrographic and tracer stations covering all the basins of the Arctic Ocean over a number of years would be of great value in understanding the flows that feed the convection region. Participation in the Greenland Sea Project is an excellent opportunity for accelerated research in an area of great scientific and naval importance.

Shelf-Basin Exchange

Continental shelves make up a large part of the Arctic Ocean (Figure 5-1). Recently, the importance of water mass transformations as the result of freezing on the shelves has been realized. The exchange of cold, saline shelf water with the deeper ocean appears to be a major process controlling the hydrographic properties of the Arctic Ocean. The Eurasian shelf appears to be two of the most vital regions for this process. A research program to study shelf-basin exchange would involve the following factors: the use of chemical tracers to better measure the bulk rates; long-term measurements of the currents at the shelf edge; and detailed surveys of the circulation and hydrography of the shelves with an emphasis on the generation and movement of the coldest, densest component of the water. This area of research shows promise for the future.

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6

OCEANIC CHEMISTRY

Oceanic chemistry is the study of the creation, transport, transformation, and destruction of substances in the ocean. Major areas of work involve:

- upper ocean processes, including photolytically mediated (light forced) processes, the marine microlayer and gas exchange;
- large scale transport of geochemicals and ventilation; and
- interaction between the solid earth and the oceans, including hydrothermal and low temperature alteration, and sedimentary diagenesis (physical and chemical changes occurring between the times of deposition and solidification).

From a chemical point of view the ocean is a "reactor" with multiple inputs: rivers, atmosphere, seafloor weathering, diagenesis, hydrothermal plumes. Within this reactor the various feeds are mixed, react with one another and, eventually, are converted into insoluble forms and removed from the system. Chemical oceanography is concerned with unraveling the various reaction mechanisms that control the distribution of chemical species within the ocean. A secondary aim is to identify past operating modes of the system through the record preserved in the accumulated insoluble reaction products, marine sediments.

What makes the field complex is that, by and large, it is not susceptible to conventional thermodynamic treatment. Organisms play an active role in most of the reactions, either directly by involvement in their metabolic processes or passively by exchange reactions with their degrading surfaces produced upon grazing, excretion, or death. Many chemical reactions are kinetically inhibited on oceanographic time scales. Conversely, atmospheric particles with extremely high surface energies produced by photon irradiation and reaction with free radicals dissolve in the surface waters to an extent well beyond what would be predicted from their bulk-phase chemistry. These phenomena are not generally amenable to laboratory study alone. Either the time scales are too long or the active surfaces cannot be reproduced artificially or sampled and then preserved in a laboratory environment. The oceans are the laboratory.

The time scales of the removal reactions vary from seconds for photolytic reactions in the surface waters to hundreds of millions of years for the most soluble species. Many elements are involved in biologically driven secondary cycles that redistribute but do not

lead to removal of the elements; i.e., most of the elements are involved in cross-isopycnal transport and are nonconservative with respect to salinity.

Hence, marine chemists are interested in the circulation and dynamics of the oceans at all scales from essentially instantaneous to geologic. All locations in the ocean are not equally "reactive." To appreciate the significance of the biologically-driven processes one must take well-known maps of surface productivity or satellite maps of chlorophyll distributions (Figure 6-1) and add the third dimension, the underlying water masses. Surface production, via its sinking debris, projects to the sea floor as columns and screens which we know from the sediment trap data are as discrete in their boundaries as is the surface activity itself. Thus, chemical signatures can be imposed locally but are transported globally. The local distribution of properties may have much or little to do with the local processes.

While the mapping of the oceanic and sedimentary distributions of dissolved and particulate species is an important activity, certain oceanic regimes can be used as "natural laboratories." Here one or only a few of the many variables are dominant, and particular processes can be studied without the obscuring effects of other phenomena. The environments can be extreme—anoxic basins or reducing pore waters in sediments—or they can be subtle—hydrothermal plumes or enclosed deeps.

It is equally important but more difficult to quantify mass fluxes associated with marine chemicals. Fluvial and aeolian inputs to the ocean are quite variable. In estuaries, chemical reactions occurring in the mixing zone between low-pH, low ionic-strength river waters and high-pH, high-salinity seawater complicate the measurements. Precise extent of dissolution of aeolian particulates has been established only recently. The hydrothermal flux is highly uncertain. Fewer than 20 hot-spring fields have been sampled, and so the complete range in compositions is unknown. Indirect methods of flux estimation disagree. Fluxes from the seafloor, due to weathering of igneous rocks and diagenetic reactions in the sediments, are areally distributed and very heterogeneous. Fluxes within the water column can be measured directly with sediment traps or calculated from dissolved distributions and circulation models calibrated with ^{14}C or other time tracers. Both methods are highly uncertain. Strong seasonality in vertical transport of biogenic particulates demands long time-series monitoring by sediment traps to get accurate estimates of mean annual fluxes, and sediment traps are known to have trapping and preservational biases.

TRENDS AND RECENT PROGRESS

Tracers and Monitoring

Marine chemists continue to provide their physical colleagues with natural chemical tracers of the circulation (nutrient elements, oxygen) to expand the dynamic range in the deep sea over that available from the more fundamental density determinants, temperature and salinity. The Geochemical Ocean Sections Study (GEOSECS) provided the first global information on transient tracers, the bomb-produced isotopes tritium and radiocarbon. Due to its very rapid rain-out and vapor exchange, tritium was injected as a "dye" in 1963, predominantly in high northern latitudes. Its propagation into the interior of the North Atlantic in the succeeding decade, as mapped by GEOSECS, qualitatively but unequivocally confirmed the deep circulation scheme developed from the distribution of steady state tracers and the then primitive theoretical models.

The extent of this penetration indicated that circulation was surprisingly rapid. The deep North Atlantic is in communication with the surface waters at high and middle

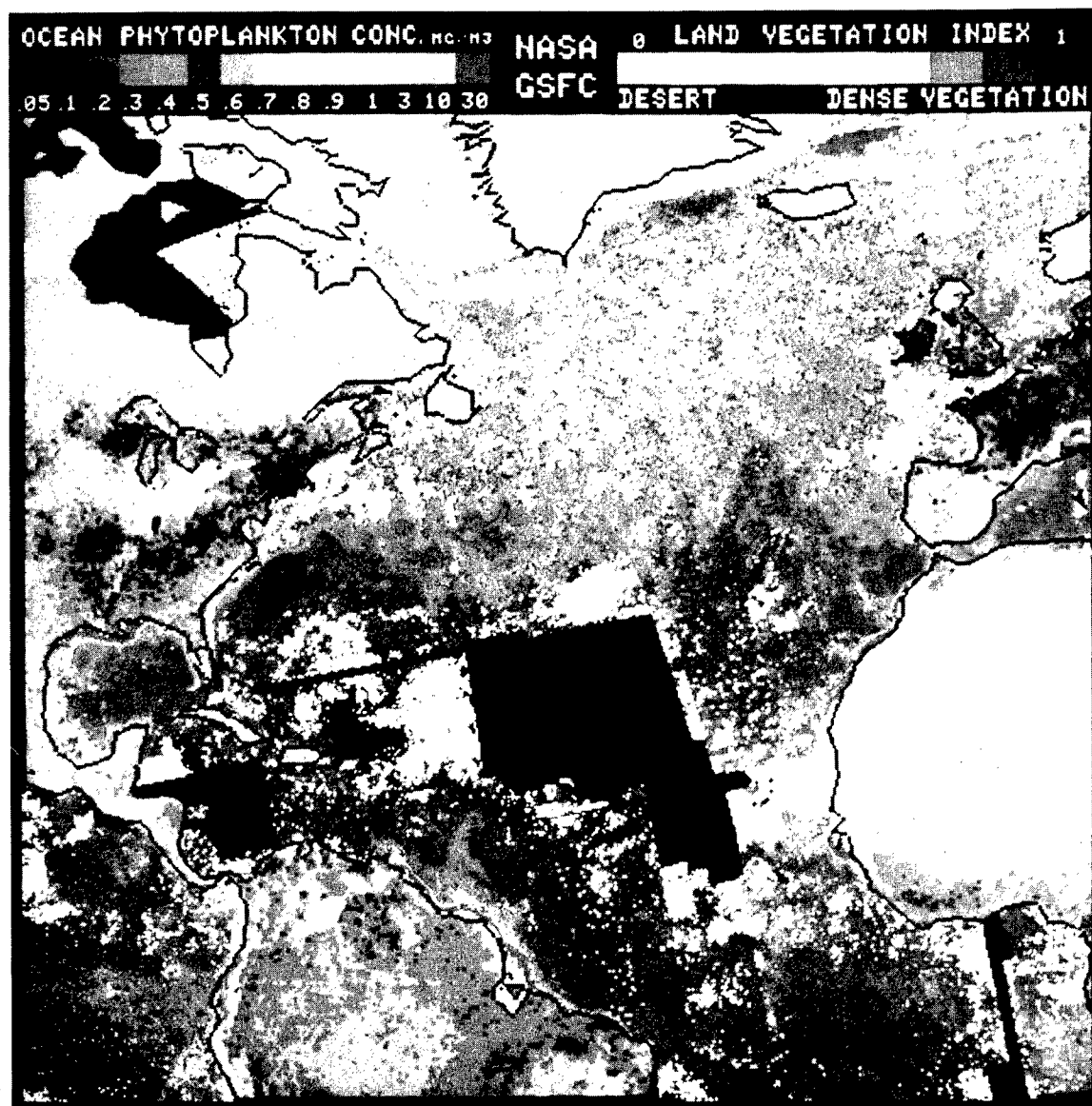


FIGURE 6-1 Satellite-derived phytoplankton pigment distribution in the North Atlantic, from the Coastal Zone Color Scanner (CZCS) instrument on Nimbus 7. The image is a composite of 31 mosaics for May 1979. (Courtesy of G.C. Feldman and C. Tucker, NASA Goddard Space Flight Center, Greenbelt, Md.)

latitudes on a decadal time scale. This rapidity was confirmed by the reoccupation of the GEOSECS section 10 years later by the Transient Tracers in the Ocean (TTO) program. The tritium "front" in deep waters had penetrated southwards by about 15 degrees of latitude (Figure 6-2).

Even more spectacular was the finding that radiocesium releases from the Windscale reprocessing plant on the Irish Sea had reached the deep western boundary current south of Greenland less than 7 years later. This immediacy of communication of environmental signals has profound climatic consequences. It is emphasized by the TTO discovery that

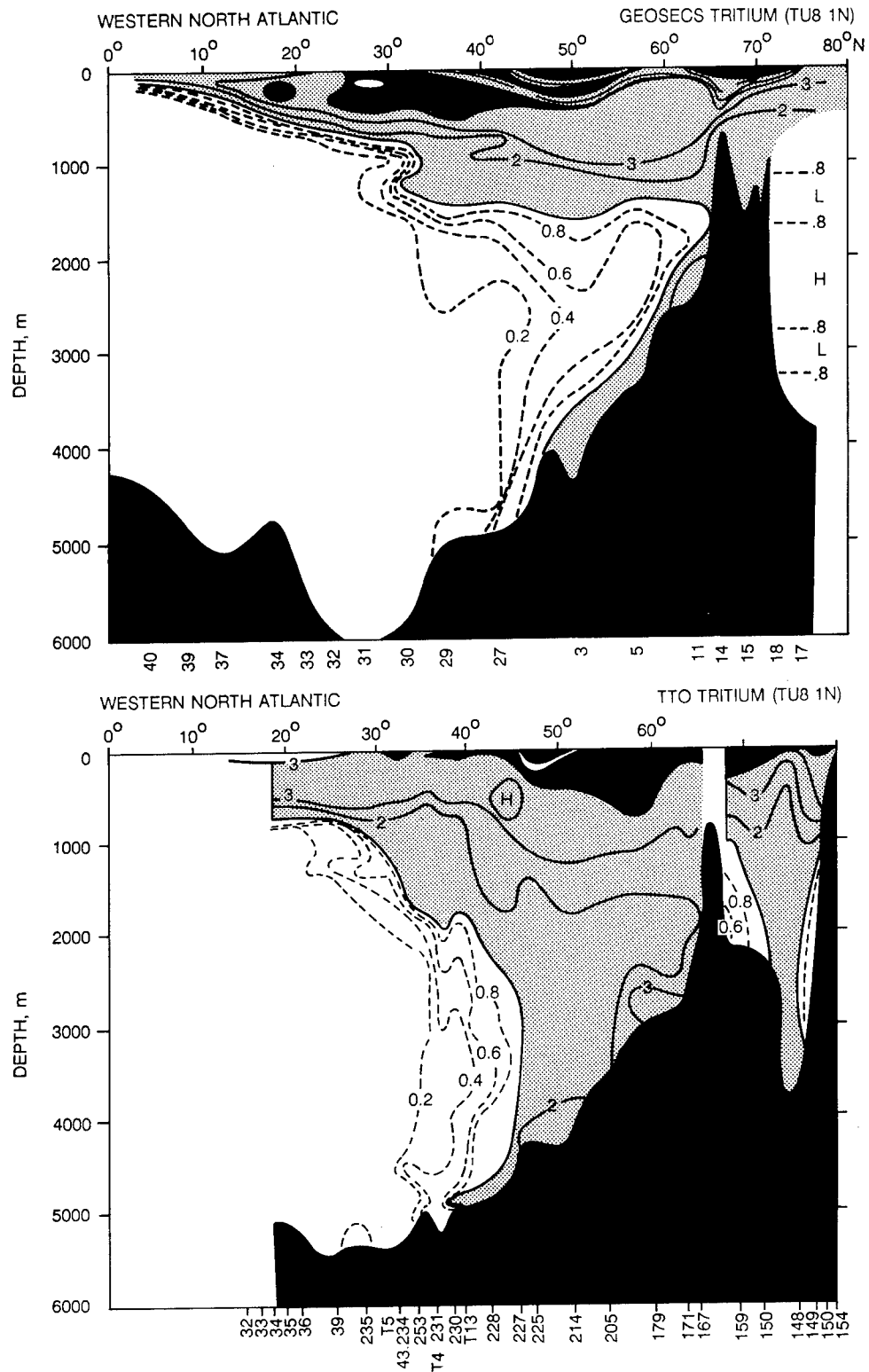


FIGURE 6-2 Increased penetration of tritium into the North Atlantic interior from the time of GEOSECS (1972) until TTO (1981) (Brewer, personal communication, 1987).

the North Atlantic had experienced a substantial drop in salinity in the period since the IGY in the late 1950s.

Toward the end of the TTO expedition it was possible to deploy a shipboard system for the measurement of another class of transient tracers, atmospheric fluorocarbons. Anthropogenic fluorocarbon solvents, propellants, and refrigerants have been released to the atmosphere in increasing amounts since the 1930s. They have very different source functions from tritium or Windscale cesium, but a comparable time scale of release. Fluorocarbon-11 and fluorocarbon-12 are now being measured at sea with comparable spatial density to nutrients.

Bomb radiocarbon exchanges much more slowly with the surface ocean than does tritium but it does provide an isotopic tag on the oceanic uptake of anthropogenic, fossil fuel CO_2 . The steady state distributions encountered in the deep sea away from areas of active convection constrain models of the oceanic circulation and suggest that the oldest waters in the deep ocean were last in contact with the surface less than 750 years ago. Attempts have been made to measure the anthropogenic CO_2 signal directly. The results have been the subject of some controversy because of large seasonal variations in surface water values in high latitudes, their inadequate documentation (especially in winter) and the long exchange time of the gas.

Another transient tracer whose development has produced some very exciting insights, especially into the marine chemistry of the upper ocean, is anthropogenic lead. It has a source in smelting and in automobile exhaust. The latter is being eliminated after a peak in the early 1970s. Lead substitutes stoichiometrically for calcium in coralline aragonite. Hence, by analyzing annual coral bands from Bermuda, one develops a record of lead in the surface waters of the Sargasso Sea over time periods as long as several hundred years. This record matches very well the estimated emission rates in the U.S. This proxy record can then be used, in combination with time-series water column profiles, to look at the redistribution of lead by biogeochemical and physical processes in the water column of the North Atlantic. From studies on its natural radioisotope, ^{210}Pb , it is known that lead is highly reactive in the oceans. The anthropogenic lead studies in the North Atlantic are the first of a highly reactive transient tracer.

This tracer work shows that effective monitoring for climatic change, natural or anthropogenic, subsumes effectively all of our knowledge of the physical, chemical, and biological environment. "Monitoring" became a dirty word in the field, perhaps because there were many misguided and ineffective efforts during the heyday of the environmental movement in the 1970s. In fact, monitoring, essentially the maintenance of absolute calibration and consistency of measurement over decades, is probably the most difficult task of the earth sciences.

Inspired by the success of the Mauna Loa atmospheric CO_2 monitoring, by the record of atmospheric pressure oscillations, by the Southern Oscillation associated with Niño Estelle, and by the documentation over a decade of the development of the ozone hole in the Antarctic, environmental monitoring is moving to center stage. It appears that the most important anthropogenic effects on the environment start with a chemical signal that then interacts with the physical environment, e.g., the atmospheric thermal budget, to produce a tangible effect. Thus monitoring for the greenhouse gases—which now include not only CO_2 but also fluorocarbons and other anthropogenic halogenated hydrocarbons, methane, and N_2O —has high priority. The combined warming produced by these gases is believed to be on the order of twice the effect of increasing CO_2 alone.

Water Column Chemistry and Particulate Material

In the last 15 years the measurement capability for stable dissolved species in seawater has improved by about eight orders of magnitude, from the micromolar range typical of the nutrients to the pico- and femto-molar levels typical of reactive trace elements. Advances for radioisotopes and trace gases have been at least as great. This incredible achievement has had much to do with the availability of advanced instrumentation but also with the intellectual demonstration of "oceanographic consistency." Elements present at concentrations 10 or 12 orders of magnitude below those of the major sea salts behave in a perfectly logical way, reflecting both the grand circulation of the world ocean and their own characteristic chemical properties, sources, and sinks. Every element of the periodic table, of whatever abundance, has potentially unique information on the chemical processes going on in the ocean.

While early work on the trace-element geochemistry of seawater was incredibly laborious, the experience gained in sample handling, sources of contamination, and detection systems has led to techniques of exquisite elegance, at the forefront of analytical chemistry as an academic field. Of necessity the "discovery phase" involved the measurement of only a few profiles, widely and often haphazardly scattered. The few people in the field, the limited availability of clean equipment, and the reluctance of the agencies to fund development work and of our colleagues to understand our problems meant that while the advances in potential sensitivity were great, oceanic coverage was painfully slow. This situation is changing with the development of technology that makes "chemical hydrography" possible. Ideally, oceanographic parameters should be measured at sea. While routine hydrography has an important role, experimental hydrography provides a very efficient way to learn about the oceans. Transient anomalies can be identified, followed and related to other parameters. What may be regarded as noise in data from discrete samples collected routinely and analyzed in the laboratory months later, may reveal exciting signals when data are available on station. While operating within the constraints of the availability of skilled analysts and the necessity that cost-effective equipment be relatively inexpensive and easy to maintain at sea, rapid advances are being made. Within a few years it should be possible to measure 20 to 30 elements at sea in close to real time.

In the early 1970s, knowledge of the distributions of dissolved species in the oceans became sufficient to show the importance of cross-isopycnal transport of material by sinking particles. In situ filtration of large volumes of water produced samples of particulates. They proved to be almost entirely of biogenic origin and to include carapaces, foram and radiolarian tests, and composite fecal pellets. A taxonomy of the latter has been developed. As the results of grazing they are complex. Since they settle rapidly and vertically they are the major conveyor of carbon from the photic zone into the interior. Hence pellets are continually being reprocessed by filter feeders and bacteria at depth. Estimates of the populations of organisms dwelling in the sub-thermocline waters and their activities require that the mid-depth suspended load be "swallowed" by these organisms several times a year at the least. Hence the entire ocean is in intimate contact with metabolic processes and the chemically active surfaces associated with them.

Rapidly sinking large particles can be collected in moored or floating sediment traps. While they generate a hydrodynamic regime around them that discriminates toward or against slowly settling material (depending on trap Reynolds number) the major proportion of the flux is collected. Time series deployments have shown that, with transit times of the order of a month, the flux to the deep sea varies seasonally, lagging only slightly the annual march in the surface waters (Figure 6-3). A bottom dwelling anemone or holothurian

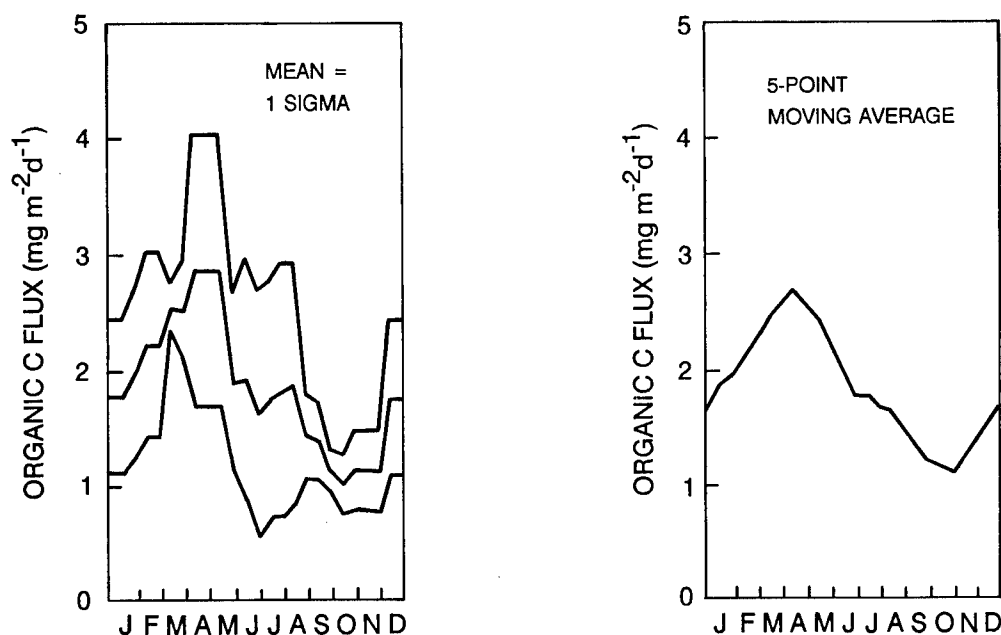
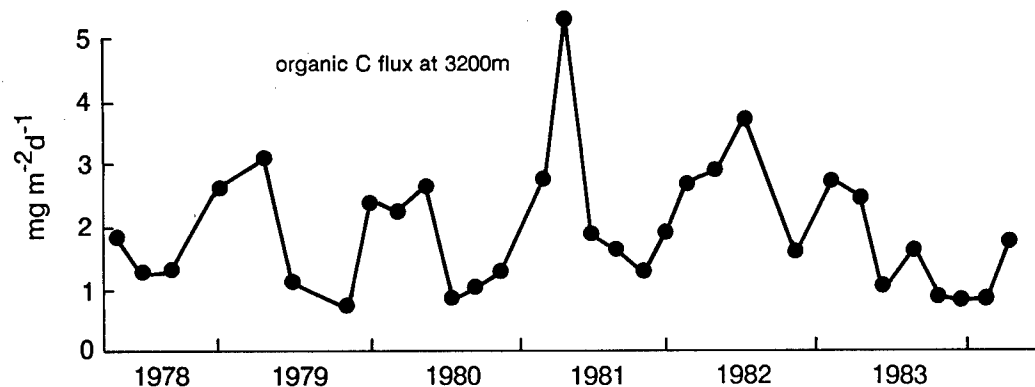


FIGURE 6-3 Seasonal variability of deep-water organic carbon flux, at 3200 m depth 45 km southeast of Bermuda, April 1973 to May 1984. The time series (top) and the composite annual cycle (bottom) are shown (Deuser, 1984).

experiences the spring bloom to much the same extent as a seabird or a tuna. Recognition of the extent to which marine chemistry is driven by metabolic energy inputs as opposed to thermodynamic free-energy transfers has been the most fundamental development of the last 15 years.

With this recognition has come an interest in the absolute values of marine primary production via photosynthesis. The first intervention into this arcane area was made by trace-element geochemists who found that, in the classical ¹⁴C uptake measurements made on plankton samples to determine organic carbon turnover, the organisms were actually

being poisoned by zinc, copper, and lead contamination of reagents and containers. Then the tracer chemists produced evidence that the oxygen balance in the upper thermocline, as calibrated by dating using tritium and its decay daughter ^3He , required carbon fluxes approximately five times higher than conventionally assumed. The latter is corroborated by the seasonal growth in oxygen supersaturations below the summer thermocline. To resolve this controversy the obvious postulate is that productivity is driven by unsteady and patchy erosion of the upper thermocline by storms, a process traditionally undersampled by oceanographers on ships and with sparse buoy networks.

Interest in productivity has led to a number of studies of the chemistry of the photic zone. Are there limiting elements, other than the classical nutrients? Is the pollution "fingerprint" resolvable? It turns out that the surface ocean is extremely noisy and energetic chemically.

The mixed layer experiences a strong seasonal cycle of productivity induced by vertical mixing and sterility caused by stratification. Many trace elements are affected, accumulating in the barren summer mixed layer from the aeolian flux and being stripped by particles produced in the blooms in fall and spring. Thus a whole season's "dose" of aeolian trace metals is stripped from the productive waters when the seasonal thermocline breaks down. A related effect must occur at high latitudes: an accumulation of dry deposition and snow occurs on the pack over winter, followed by rapid introduction into the spring low-salinity layer upon melting. Particularly in areas receiving pollutants, trace metal load must episodically be much more severe than would be anticipated from the usual randomly collected values.

Upper Ocean Processes

The exchange of gases between the ocean and the atmosphere has received renewed attention over the past few years in relation to the global carbon dioxide problem and controversy over levels of primary production. Nearly every biogeochemically important system has a gas phase and is affected by gas exchange with the atmosphere. The converse is that gas exchange fluxes are proving to be important calibration tools for estimating the rates of some biological and chemical processes in the mixed layer. Attempts to identify gas exchange dependence on wind speed have met with limited success on "local scales," although the climatological dependence appears more robust. It now appears from several field studies that gas evasion rates scale with the one-half to two-thirds power of the Schmidt number (the ratio of viscosity to gas diffusivity). Large, circular wind tunnels for determining gas exchange rates in the laboratory have yielded some understanding of relationships between physics and chemistry of these complex processes, but there still is concern about replication of the marine environment. The role of natural surfactants and bubbles has yet to be well resolved, but it is clear that they can be important under some circumstances.

Large-Scale Transport

Inferences regarding the rates of biogeochemical processes within the water column are often drawn from mean tracer distributions. In many ways, this approach is the only viable one for the large-scale spatial and temporal integration of processes that are strongly variable. It addresses questions that affect the role of the ocean in the global climate system, as well as the large scale transport and cycling of the elements, and in particular the carbon cycle. Tracer techniques therefore will play an important role in two major international

initiatives: the World Ocean Circulation Experiment (WOCE) and the Global Ocean Flux Study (GOFS). The cross-linkage between carbon dioxide and the glaciation/deglaciation cycles as implied by ice-core data, and the inferred control of atmospheric carbon dioxide inventories by oceanic nutrient cycles (particularly in polar/and subpolar domains) make the study of ocean transport of geochemicals particularly important.

Significant advances in the field over the last several years include the application of radiocarbon budgets to refining estimates of rates of North Atlantic Deep Water (NADW) formation and constraining equatorial upwelling rates and abyssal ventilation rates. Observation of a plume of primordial ^3He in the Pacific has led to the rather surprising conclusion that the abyssal flow in the South Pacific does not follow accepted circulation theory. This discrepancy was later rationalized as being due to a flow induced by the mid-depth injection of hydrothermal buoyancy. Tritium (and later tritium- ^3He) dating has been used to demonstrate that ventilation of the main thermocline in the North Atlantic is about three times faster than can be accomplished by Ekman pumping alone. The detection limit for tritium has also been improved by nearly two orders of magnitude using mass spectrometric techniques. The tritium- ^3He technique was used to estimate oxygen consumption rates, which in turn initiated the primary production controversy. It is important to note that the latter two accomplishments were made possible by early support from the ONR in developing the tritium and ^3He techniques. An exciting new development in tracer oceanography involves the tracking of the Windscale radioactive effluent into the Norwegian and Greenland seas, and subsequently into the northern North Atlantic. This unique and well-documented "point source" provides us with a unique opportunity to study deep-water formation. Development and testing of numerical models that specifically include transient and natural tracers is now gaining momentum.

The TTO expeditions in the earlier part of this decade have built on the pioneering work of the GEOSECS program, applying new tracer measurement techniques and denser sampling strategies to the North Atlantic. A detailed isopycnal analysis of the distribution of nutrients in the world ocean, using advanced alkalinity titration data, has led to revision in the Redfield ratio, which stood for half a century. Combining high-precision carbon dioxide measurements with those of radon has permitted the mapping of carbon dioxide fluxes across the ocean-atmosphere boundary for the first time. Evidence for decadal variations in the salinity field in the North Atlantic has come from comparison of the TTO with IGY hydrography, suggesting strong climatic modulation in modes and rates of NADW formation. Shore-based analytical data from TTO expeditions are only now becoming available, so much more literature will be seen over the next few years.

Several new tracers have emerged from the TTO programs as promising tools for studying ocean circulation and ventilation. Shipboard measurements for fluorocarbons (freons) in small samples permit near real-time determinations of a transient tracer. Potential results for feedback between data and sampling and for measurement of mesoscale features. The ratio of fluorocarbon-11 to fluorocarbon-12 further provides a dating tool on 5- to 10-year time scales and, combined with tritium- ^3He dating, provides a powerful technique for studying circulation, ventilation (see, for example, Figure 1-2) and the rates of chemical transformations on 1- to 50-year scales. At the other extreme, ^{39}Ar requires 1200 kg of seawater but has the ideal characteristics of being a natural, steady-state noble gas with a half-life of 269 years. Thus it is evolving as a valuable tool for studying the global thermohaline circulation and abyssal ventilation, although the data base is still meager because of limited analytical resources. Finally, ^{228}Ra has evolved as a unique basin-scale tracer of lateral processes because of its approximately 5-year half-life and its production in sediments.

Vertical transport by particles is, of course, an important part of the global circuit for many geochemicals. Direct measurement of particle flux has long been supported by the ONR. Steady progress has been made in the development and design of effective traps, although problems still exist with sample preservation and unbiased collection, particularly in shallow deployments. Perhaps the most striking development in the field has been the documentation of seasonal variations in particle fluxes at 3 km depth in the Sargasso Sea (Figure 6-3). A unique long-term time series is evolving, and coupled with other measurements, interesting insights are being gained in the nature of particle formation, transport, and destruction. The combination of water column and sea surface measurements with state-of-the-art particle trapping techniques has been utilized effectively in the VERTEX program as well. Within the water column, exchange of dissolved species with particles has been effectively studied using Th- and U-series isotopes, enabling first-order reversible equilibrium modeling of distributions to establish sorption rates and kinetics.

Progress in the application of gas chromatography of metal chelates has permitted shipboard analysis of Al, Be, and Se, as well as Ge and Hg. Oceanic distributions of these elements are now providing insight into their geochemical behaviors.

Interaction with the Solid Earth

The discovery and subsequent intensive studies of submarine hydrothermal vents have provided strong stimulus to the field. A substantial number of vent sites have been discovered in a variety of ridges. Armed with knowledge of the basin and global scale ^3He flux, estimates of the global elemental exchange fluxes of several elements have been made using ^3He -element correlations at the vent sites. Estimates seem credible for many major elements, but for others are inconsistent with large-scale budgets. A number of concerns need resolution. The first arises from the potential decoupling of ^3He from the element in question, due either to diffusive steps or water-rock ratio limitations. The second results from the possibility that the mid- to low-temperature stages of water-rock interaction result in different relationships between the element and the "calibration isotope" (^3He). Finally, an adequate understanding of the fundamental physical and geochemical nature of the water-rock interaction has not been advanced to explain inter- and intra-vent variability, or to predict long-term evolution and the character of geochemical exchange in mature hydrothermal systems.

The hydrothermal effluent itself is an interesting natural laboratory for chemical processes. Here a promising tool for characterizing elapsed time and amount of dilution involves the measurement of ^3He and ^{222}Rn . Evolution of the absolute concentration of ^3He yields the dilution and permits the normalization of the ^{222}Rn (half-life of about 4 days) content to date the effluent. This clock-dilution meter is being used to determine rates of precipitation and scavenging of Mn.

Recent work has suggested that a significant fraction of benthic oxygen consumption occurs within sediments. This finding implies an equally direct role of sediments in controlling water-column inventories of other substances, via the diagenetically related fluxes of elements into and out of the sediment. Attempts have been made to use pore water profiles to determine these fluxes, but the possible presence of pore-fluid advection, as hinted at by the curvature in temperature and helium profiles, would require a major reassessment of the magnitude of these fluxes. The pore fluid velocities thus far determined are uncomfortably large, and hence require independent confirmation. Application of microelectrodes is providing detailed data on the distributions of oxic and suboxic zones within the sediments. Of particular interest has been the nature, magnitude, and influence of bioturbation on

sediment structure, zonation, and sediment-water fluxes. Benthic respirometers and other flux chambers have been used effectively over the past several years.

NAVAL RELEVANCE

The immediate naval relevance of chemical oceanography has grown over the past years, with increasing attention to organic films. Previously the field showed little prospect of general operational impact except as a tool for addressing problems in physical oceanography (for example, to trace water masses) or biological oceanography (for example, differential species response to changes in nutrient levels).

The Law of Constant Proportion applies so universally to the major chemical components of seawater that only variations in trace-level components showed potential value as indicators of anthropogenic activity. This capability is, of course, of direct interest to both submarine detection and security, but the unavailability of field-reliable, accurate methods for making real-time measurements, either remotely or while under way, has made it impossible even to properly study background levels for all but a few species of interest. This inability has generally limited naval application of chemical oceanography to intelligence or pollution monitoring roles where long-term, off-line results were useful. Another formidable problem has been the lack of verified reaction-diffusion models useful at search scales (meso and small). It should be noted however, that this "negative" result is in itself relevant to system designers, and the topic was in fact pursued by ONR in specific response to their input. Results from recent research in marine photochemistry are relevant for similar reasons.

Organic films are of naval interest primarily because of their postulated effects on the emission and backscatter of energy from the sea surface. Films of man-made surfactants have been shown to produce visible modulations of surface glitter and to reduce ambient acoustic energy generated at the sea surface. Naturally occurring films are believed responsible for the phenomenon of sea slicks, and for the presence in some images of an apparent ship wakes, visible for tens of kilometers in the glitter pattern.

Little is known about organic films in the ocean, but if they are as common as some believe and if their physical properties are as some hypothesize, then films may have significant influence on the formation and evolution of the capillary waves on which most of our radar-based methods of ocean remote sensing rely. Consequently our models for radar clutter for relating radar data to internal-wave induced and bottom-modulated current fields may require modification. In this sense, chemical oceanography is once again in a support role to another discipline, but the investigation of the composition, physical properties, and "life cycle" of films will have to come from chemical oceanography.

Other areas of oceanic chemistry with historical or current significance to naval operations are the effects of seawater chemistry on sound speed and attenuation, and various chemical aspects of biological productivity, pollution, visibility, corrosion, fouling, and bottom stability. The acoustic and bottom aspects of oceanic chemistry have been emphasized less in recent years; the pollution, materials, and particulate aspects have held constant. Only surface chemistry, photochemistry, and films have been of increasing interest, spurred by remote sensing questions.

PRESENT ONR PROGRAM

Because of the limited naval relevance long perceived for marine chemistry, ONR supports little of the effort viewed as the most important by academic chemical oceanographers,

and reviewed in the previous section. For example, much of the ONR program is focused on surface films. Long known to sailors, films are ubiquitous in satellite sunglitter patterns and reveal complicated swirls and long-lived ship wakes, neither of which was previously recognized. Until ONR stimulated work following the first satellite pictures, the dynamics and chemistry of the films received only passing attention from university chemical oceanographers.

Films determine the surface tension and hence roughness and wind drag of the sea. Chemically, such a film can be expected to have a significant complexing capacity and to be photochemically active. It is also the recipient of the aeolian flux, a major delivery mechanism for inorganic and organic material to the remote ocean. A combination of high surface-energy material, produced by reactions in the atmosphere, and the unique environment of the surface film may greatly enhance the efficiency with which the aeolian particulates are dissolved on contacting the sea surface.

While aeolian input to remote areas is usually easy to identify, little is known about the mechanisms by which coastal waters mix out into the deep sea.

The ONR has been particularly catalytic in spurring new activity and the application of new techniques in determining the effects of solar radiation on biological and chemical processes in the upper ocean. Although much of the progress in photochemistry over recent years has been coupled to work in freshwater and terrestrial systems, significant strides have been made in the sea. Dissolved organic matter (in particular humic substances) and detritus are believed to be the two major chromophoric substances in natural waters. The proposed formative process of marine humic substances by photo-oxidation of triglycerides and polyunsaturated fatty acids has stimulated much interest, along with other work on the structure and behavior of marine humic and fulvic substances. It has been suggested that the major photo-reductive sink for oxygen in the euphotic zone involves humic substances. Evidence suggests that this mechanism is significant relative to biological pathways. The relation of light energy to the long- and short-lived products and intermediates of photolytically produced chemicals (e.g., hydroxyl radical, superoxide, low molecular weight carbonyl compounds, and hydrogen peroxide), to the degradation of pigments, and even to the cycling of trace metals is being investigated. Promising techniques in the field of photochemistry include the use of aromatic radical scavengers, nitroxide spin trap compounds, and laser flash kinetic spectroscopy. Development of mixed layer models incorporating simplified photochemical mechanisms is also proceeding.

The fates of anthropogenic, primarily petroleum-based, compounds are linked to photo-oxidative processes. The persistence and evolution of these substances and their byproducts are of considerable interest because of their influences on biota and on the physical and chemical character of the ocean surface. Photosensitizers (especially humic substances) influence major ion chemistry and interact with bacterial processes to play a complex and important role in accelerating degradation.

Work on surface films has been stimulated and supported by the ONR. Characterization of the composition of organic films in the marine microlayer has progressed, although much work remains in classifying and identifying the organic compounds involved, and in determining the relationship between biological activity (planktonic and bacterial) and these films. It appears that lipids do not play as large a role as do carbohydrates and proteins. The roles of surfactants, small bubbles and macromolecular polymers are indisputably critical to the process of film formation, but more work is needed to build an integrated understanding. This area of research is particularly exciting in that it involves the complex interaction between biology, physics, and chemistry in the creation, maintenance, and

destruction of the microlayer. In situ measurements of physical properties of the surface microlayer are being tried using laser techniques.

Cycling of reduced gases has been studied with support from the ONR over recent years. Distributions of methane and hydrogen have been mapped, as have their temporal variations. Such observations provide clues as to source and sinks, and measurements of possible intermediates (e.g., acetate and trimethylamine for methane) are illuminating various biogeochemical pathways. Recently, dimethyl sulfide and its role in the global sulfur cycle has received considerable attention, along with related sulfur compounds. The production of dimethyl sulfide in coastal environments as well as in the open ocean has been studied extensively by a number of groups. It has been proposed that the photooxidation of this gas within the atmosphere provides nucleation sites for formation of marine fog and clouds, and hence may play an important role in modulating climate through the oceanic albedo. The possibility of feedback loops through insolation, biota, and nearsurface ocean physics provides an extremely exciting field of research for the future.

CURRENT PROBLEMS

As in all the experimental sciences, marine chemistry is being driven by the technological explosion. To understand the frenzied pace of progress in the field one has only to compare Wyrski's atlas of the Indian Ocean Expedition, representative of the early 1960s with the GEOSECS atlases of only 10 years later. Another step function in capability is being approached as accelerator mass spectrometry (AMS), inductively coupled plasma/quadrupole mass spectrometry (ICP/MS), flow injection analysis, high pressure liquid phase and supercritical phase chromatography, and other revolutionary analytical techniques become available. Marine chemists are at the cutting edge of chemical measurement and, for the last 10 or 15 years, measurement has been driving the science.

Marine chemistry is in a phase of accelerating growth both technically and intellectually. Unless some critical problems such as manpower, facilities, and theory are resolved, this potential accelerated growth will be retarded. It is common among the small group of marine chemists leading the analytical revolution to hear the claim, "Give us the support and we can measure anything in the sea." It is almost true, which means that the time is near for formal solution of the inverse problem; that is, the unraveling of the chemical processes going on within the oceans has to be approached as an inverse problem controlling the distributions themselves. As a practical matter we use the myriad chemical properties of the elements, their valence states, compounds and isotopes as probes of the active reaction mechanisms.

Each new measurement of an element—a valence state, a compound, or an isotopic ratio and its fractionations—adds a constraint to the inversion. How can the entire battery of capabilities be maintained (difficult measurements are made by skilled individuals using state-of-the-art equipment), and how can this battery be brought to bear on a particular problem or geographical area or region in temperature-salinity parameter space? Conversely how can it be decided what fraction of the total capability should be brought to bear on a particular problem? How is "overkill" to be defined?

A second key problem is the recruitment of top people to the field from the traditional undergraduate disciplines of the physical sciences and engineering. Unlike oceanography, these parent disciplines are organized as professions based on their historical status in academia, business, and government. The appreciation of oceanography as a field of scientific endeavour is not widespread. Thus, the students we are recruiting from the parent

disciplines are following career tracks that are exceptions to the "professional" norms in their fields.

How to deploy these new tools, or "where and when should measurements be made," is now a major issue. It is safe to say that the application of transient tracers in oceanography is being held up because nobody can give an explicit and defensible answer to the question, "how densely must you sample in space and time?" This question involves commitment of ships, people, and facilities, i.e., potentially enormous financial support. The answer is likely to come from more data and from diagnostic models of the ocean circulation. As recent history has shown, the intuition of even the most distinguished practitioners does not always pass the muster of his or her peers. Nevertheless, discoveries continue and the unexpected and unpredictable are still important.

GROWTH AREAS

Marine Chemical Modeling

Certain problem areas in marine chemistry now seem mature enough to be tractable to numerical and analytical modeling. An overt, substantial effort to incorporate the available data sets would be cost efficient in terms of designing future sampling programs. In a field like ocean chemistry, in which advances are so dependent on new instrumentation and new data, any opportunity to make the most of the already-obtained data must be exploited.

The complex, nonlinear interactions between the chemical, biological, and physical forces in the upper ocean can only be fully studied within the context of diagnostic numerical models. There is a broad range of scales (both space and time) involved in such processes. For example, the global-scale thermohaline circulation is responsible for modulating the annual/decadal flux of nutrients to the oceanic upper layers. The intermediate scale mechanisms of mesoscale eddies and winter convection as well as mixed layer/seasonal thermocline dynamics are responsible for controlling the flux of nutrients into the mixed layer. Finally, on the smallest scales, nutrient uptake, excretion, and predator-prey interaction connect the biota to the geochemical cycle. These complex scale-dependent interactions provide a fertile ground for making progress in our understanding of marine chemistry. Further, extension of prognostic modeling to the biogeochemical character of the upper ocean in response to physical (meteorological and climatic) forcing will prove a powerful tool as guidance for field sampling strategies, and possibly to predicting the biological, physical, and optical character of the ocean surface for operational purposes. A particularly fruitful long-term goal may be to model the role of biogeochemical control of gases such as dimethyl sulfide (and their exchange with the atmosphere) that are important sources of nucleation sites for the formation of marine fog and clouds.

The volume and character of data expected to be generated by the GOFS and WOCE will require assimilation by numerical methods. The development of assimilative and inverse models within the field of geochemistry will be a demanding, but rewarding, task. The former is mandated by the broad variety of information (in character, quality, and quantity). The latter, especially, requires the use of nonlinear optimization theory, and because of the double-edged problem of imperfectly understood or characterized boundary conditions, incorporation of techniques from other fields (e.g., control theory) may be fruitful.

The Effects of Measurement Advances

Chemical oceanography, arguably more than any other subdiscipline, has made major measurement advances over the last decade. The ranges of properties that can now be

measured (both in character and in abundance, down to attomolar range), the spans of time (from nanoseconds for photochemistry to centuries for large-scale cycling of the elements), and the breadths of space (micrometers to megameters) makes it an intellectually demanding field. Development of data-assimilating and measurement-guiding models is therefore a high priority task. Infusion of modern computer techniques (for data acquisition and reduction, and for experiment control), and state-of-the-art analog electronic circuitry into the discipline would be beneficial.

An acute need for large-scale chemical oceanographic modeling has been made apparent by planning of the NSF-sponsored WOCE and GOFs programs. Several meetings have been held and documents produced to chart a path toward development of the needed modeling capability. To a great extent this path follows extant physical oceanographic models and relies heavily on numerical techniques to incorporate the additional sources and sinks of chemical reaction and gravitational settling. Although much remains to be done, the effort already has been focused by extant or nascent programs.

By contrast analytical modeling that realistically incorporates physical and biological transport and chemical (including biochemical) transformations on the shorter scales characteristic of these processes and of their interactions is barely at the conceptual stage outside existing ARIs in chemical and biological oceanography. Point source or plume models for conservative or simply (i.e., with first-order kinetics) decaying material exist, but even they are not well tested with respect to such issues as mixing (producing intermediate concentrations) versus stirring (producing interleaved parcels of high and low concentrations). Despite the fact that it has been made apparent in the last decade that little of the ocean's chemical distributions can be predicted from straightforward thermodynamic calculations, models that meld state-of-the-art knowledge of physical and biological oceanography with reaction kinetics are nonexistent. Without such models it is impossible to answer questions of how many samples are needed or to what sampling precision analytical approaches should be driven. In short, the ability to measure is beginning to outstrip the ability to rationalize measurements.

The ONR chemical oceanography program is unusually well poised to remedy this problem because of ongoing and planned ONR modeling efforts at similar scales in biological and physical oceanography as well as in sediment (particle) transport. Such models would provide a ready means of influencing the evolution of global-scale geochemical programs toward phenomena of naval relevance. The provision of mechanistic process models at small scales and mesoscales is certain to provide more accurate and probably more efficient parameterizations than are now embedded in regional and global geochemical models. Thus such models are likely to be picked up quickly by programs such as GOFs.

Education

The primary impediment to progress in marine chemistry has been (and will continue to be) the complexity of the systems studied, the paucity of data to characterize well-modeled systems, the paucity of simple, evocative models to guide the study of other systems, and an increasing lack of trained people to do the intellectual work. Marine chemistry lies at the nexus of physical, biological, and even geological processes, so that problems often have many facets and involve the complex interaction of many space and time scales. The strategy has been to stimulate the development of sophisticated instrumentation and measurement techniques, a complexity that puts a substantial stress on the training of students and on their background. Further, the potential for growth lies at the interfaces between the "disciplines," i.e., in areas one usually regards as the intersection of chemical with physical,

biological, and geological oceanography. We need to accommodate this complexity and provide a firm base upon which to build experimental programs, and for the development of educational programs that are commensurate with the breadth and content of the research programs.

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